BENEATH THE BOTTOM LINE: AGRICULTURAL APPROACHES TO REDUCE AGRICHEMICAL CONTAMINATION OF GROUNDWATER

Volume II--Contract Papers

Part C: Nutrient Management

1. Legumes as a Nitrogen Source: Implications for Nitrate Contamination of Groundwater -- G. H. Heichel

2. Improving Livestock and Poultry Management Practices to Reduce Nutrient Contamination of Groundwater -- John M. Sweeten

3. Sludge, Slurry, and Compost: Management of Land Application -- James A. Moore

4. The Role of Retail Fertilizer Dealers in Reducing Groundwater Contamination: A Focus on Educational Needs -- Ronald J. Williams and James M. Ransom

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LEGUMES AS A NITROGEN SOURCE: IMPLICATIONS FOR NITRATE CONTAMINATION OF GROUNDWATER

by

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ABSTRACT

The quality of ground water for human consumption and for irrigation of agricultural crops is of substantial national concern. Water quality may be impaired by enrichment with nitrate, a naturally-occurring form of nitrogen that is the major limiting nutrient to a productive and profitable agriculture. Commercial fertilizer and livestock wastes are thought to be the major sources of nitrate in ground water. However, nitrate can be derived from agricultural crops like legumes, which remove nutritionally inert and environmentally benign gaseous nitrogen from the atmosphere and convert it into forms nutritionally essential for plant and animal life.

Living legume crops and their decomposing residues may be sources of nitrate for loss to ground water. The potential for loss of nitrate from legumes to ground water is poorly understood in comparison to losses from other sources. The purposes of this investigation were to review the fixation of atmospheric nitrogen by legumes, analyze how the management of legumes affects the return of nitrogen to the soil, evaluate the substitution of legume nitrogen for that from commercial fertilizers, assess the scientific evidence for loss of nitrate derived from legumes to ground water, and propose policy initiatives relevant to legume usage on cropland.

The limited results on nitrate loss from legumes indicate that, with certain exceptions, nitrate loss from living or destroyed legume stands is usually less than, and occasionally similar to, losses from unfertilized and fertilized grain crops. There is limited evidence for appreciable nitrate loss from living legume stands attributable to excessive application of irrigation water, lack of ground cover

following legume stand destruction, or lack of synchrony between legume residue decomposition and nitrate uptake by a following crop. Definitive data are lacking.

Policy implications of nitrate loss from legumes were assessed. Recommendations include adopting a rational annualized rate of nitrate leaching from agricultural land to ground water as a policy benchmark, crafting complementary commodity support and water quality legislation, devising incentives to facilitate adoption of legume-based crop rotations where they would advance social goals for water quality, and targeting new research at developing the database and technology necessary to bring annualized nitrate leaching losses from cropland into compliance with a policy benchmark.

I. INTRODUCTION.

The quality of ground and surface water is an issue of past (Viets and Hageman, 1971) and current (Keeney, 1986; Hallberg, 1987; Joint Council, 1988) national concern. Agricultural activities were identified as sources of nitrate-nitrogen (hereafter, nitrate) and other chemicals in ground water (Keeney, 1986; Hallberg, 1987). Although nitrate is a chemical of natural origin, enrichment of drinking water with this nitrogen (N) form may endanger humans (USEPA, 1982). The evidence that production of crop and animal commodities may introduce nitrate into ground water has led to the development of national research strategies to address the nitrate-ground water issue (USDA-ARS, 1988).

Mineral N, chiefly in the form of nitrate from commercial fertilizers or animal wastes (Fig. 1), is thought to be the major source of nitrate appearing in ground water. However, nitrate conceivably can be derived from crops like legumes, which remove ("symbiotically fix") nutritionally inert and environmentally benign gaseous N_2 from the earth's atmosphere and convert it into nutritionally active forms necessary for plant growth. Decomposition of legume residues, enriched in N by symbiotic fixation, might mineralize nitrate for movement to ground water. The purposes of this communication are to review the fixation of atmospheric N_2 by legumes, discuss how legumes influence the quality of soil, consider how legumes provide N to cropping systems, evaluate the evidence for nitrate release from legumes to ground water, and assess relevant policy issues. The availability of recent and specialized reviews on many topics germane to the foregoing purposes (Keeney, 1986; Hallberg, 1987; Heichel, 1987b; Hesterman, 1988;

Radke et al., 1988; Russelle and Hargrove, 1989) argues for an interpretation and synthesis of current knowledge rather than an extensive literature review.

II. DINITROGEN FIXATION IN THE N CYCLE OF CROPPING SYSTEMS.

A. Dinitrogen fixation: process and sources. Biological dinitrogen (N_2) fixation, the reduction of atmospheric N_2 to ammonia, is a process carried out by several species of bacteria, algae, and fungi that exit either as free-living organisms or in beneficial (symbiotic) associations with several species of herbaceous and woody crops. The general reaction for N_2 fixation, catalyzed by the nitrogenase enzyme, is

$$N_2 + ATP + e^- + H^+ \text{--------} > NH_4^+ + ADP + P_i + H_2$$

In this reaction N_2 is nitrogen gas, ATP is adenosine triphosphate, e^- represents an electron, H^+ a proton, NH_4^+ is the ammonium ion, ADP is adenosine diphosphate, P_i is inorganic phosphate, and H_2 is hydrogen gas. The stoichiometry of the reaction varies with species and with the number of protons reduced simultaneously with N_2.

Numerous species of non-photosynthetic and photosynthetic bacteria, actinomycetes and blue-green bacteria fix N_2 (Sprent, 1979). Some bacteria and actinomycetes such as Azotobacter, Clostridium, Pseudomonas, Desulfovibrio, and Corynebacterium inhabit agricultural soils and reduce N_2 under aerobic and anaerobic conditions. Blue-green bacteria are even more widely adapted than N_2 fixing bacteria, inhabiting soils and aquatic habitats that are generally above pH 7. Dinitrogen fixation by free-living organisms is generally more important in natural, unmanaged habitats than in managed agricultural systems. The rates of N_2 fixation by free living organisms are slow and consequently are not easily quantified on a land area basis. Flooded

rice soils in Russia fixed up to 20 lb N/acre/month (Mishustin and Yamtsev, 1976) for a growing season of unreported length. For upland agricultural soils, rates of N_2 fixation by free living organisms depend upon edaphic conditions and are thought to range from 0.5 to 8 lb N/acre/month (Mishustin and Yemtsev, 1976); these values represent no more than 6% of the mean net input (about 130 lbs N/acre) of biologically fixed N_2 into soils grown to legume crops.

Certain nonphotosynthetic bacteria, notably Azotobacter and Azospirillum, may live in the mucigel layer on plant roots or within the root cortex. In such associations the plant is the carbon source for the bacterium and the bacterium may serve as a source of reduced N compounds and other growth promoting materials such as hormones for the plant. The benefits of associative fixation by Azospirillum are thought to accrue mainly in tropical habitats. In soils of the U.S. corn belt, activity of introduced strains of Azospirillum with corn was minimal, perhaps due to the lack of adaptation of the bacteria (Albrecht et al., 1981). Azotobacter reportedly colonizes corn roots (Ela et al., 1982), but the significance of this association is hard to demonstrate. Although the N_2-fixing ability of associative organisms is unquestioned, the potential contributions of this process to U.S. agriculture are not encouraging. Rates of associative N_2 fixation range from 1 to 15 lb N/acre (Vose et al., 1982), and represent no more than 11% of the mean net input of biologically fixed N_2 into soils grown to legume crops.

Three types of symbiotic (mutually beneficial) associations are important to agriculture. The symbiosis between agricultural legumes and root-nodule forming bacteria of the family Rhizobiaceae are of greatest importance. In these associations the free-living (non-N_2-

fixing) form of the bacteria elicits the formation of tumor-like growths called nodules on roots of compatible legumes. Once the nodule is formed, a specialized bacterial form (the bacteroid) synthesizes nitrogenase and catalyzes the reduction of atmospheric N_2 to NH_4^+. The plant is the carbon source for the bacteria, and the bacterium provides a nutritionally valuable form of N to the plant. Rates of fixation in this system range form 4 to 277 lb N/acre/growing season, average about 130 lb N/acre/growing season (Heichel, 1987a) and will be discussed more thoroughly below.

The symbiotic association between the blue green algae, Anabaena, and the aquatic fern, Azolla, is of secondary importance. The Anabaena resides within the leaf cavity of Azolla, with the two partners of the symbiosis exchanging carbon and N as described above for rhizobia and legumes. This symbiotic association achieved agricultural significance in flooded rice paddy soils of Vietnam and China where the fern is cultured in ponds and added to rice paddys after transplanting (Lumpkin and Plucknett, 1980). For rice grown in paddys under U.S. conditions, rates of 36 to 45 lb N/acre/35 days were measured (Talley et al., 1981). The potential application of N_2 fixation by the Azolla-Anabaena system to U.S. agriculture is uncertain. Moreover, the potential for using stem-nodulating legume trees or shrubs (e.g. Sesbania spp.) as a green manure in summer fallow in U.S. cropping systems is unknown. These species are primarily adapted to tropical regions and find use in green-manuring of rice paddys (Alazard et al., 1988).

Actinorhizal associations, nodule-forming symbioses between actinomycetes such as Frankia and non-leguminous angiosperms such as alder, are currently of least importance of the three symbioses

discussed for cultivated agricultural croplands. The association is of greater importance for natural and forest habitats, where it may contribute N to neighboring non-N_2-fixing species. The association becomes agriculturally important when ruminant farm animals browse such woody plants as Alnus and Purshia. Annual N_2 fixation rates from 50 to 178 lb N/acre were estimated for Alnus; rates for other nonleguminous angiosperms range from 0.1 to 53 lb/acre/year (Akkermans and Van Dijk, 1981).

N_2 Fixing Crops: Distribution and Amounts of N_2 Fixed.

Food and feed crop legumes are the N_2-fixing species of greatest agricultural importance in the U.S. (Table 1) and totaled at least 89.7 million acres in 1986 (USDA, 1987). The tabulated summary excludes areas of some vegetable beans (e.g. lima bean, butter bean) harvested for human food and of some forage legumes (e.g. red clover, birdsfoot trefoil, sweetclover, annual clovers, vetches) grown for animal feed or on farmland withheld from production. The area planted to such crops may total another 37 million acres, but accurate disaggregated statistics of its use are not available.

Soybean, the most important grain legume in the U.S., is adapted for growth from the Gulf coast to Canada, and from the Atlantic seaboard to the eastern Great Plains. The U.S. Department of Agriculture tabulates soybean production statistics for 29 states (USDA, 1987); the Corn Belt states of Illinois, Iowa, Indiana, Ohio, Missouri, and Minnesota plus Alabama and Arkansas grow 90% of the crop. The main ecological factors limiting soybean distribution are water and photoperiod. The crop is recommended for level to gently sloping ($\leq$ 3%) soils to guard against soil erosion. The majority of the crop is grown

in a 2-year rotation with corn (i.e. corn-soybean, then repeat), although soybean is double-cropped with winter wheat in southern and southeastern states. The crop is an annual.

Alfalfa, a perennial, is the most important forage legume in U.S. agriculture. It is adapted for growth from new England and the Middle Atlantic States through the Great Plains to the West Coast, from the Mexican border to Canada west of 96° W longitude, and from 36° N latitude north to Canada east of 96° W longitude. Small areas are grown in Florida, Georgia, Louisiana and other southern states. The U.S. Department of Agriculture tabulates alfalfa production statistics for 43 of the 48 contigious states, which illustrates the range of adaptation of this species. The Corn Belt and Lake States of Iowa, Michigan, Minnesota, Nebraska, and Wisconsin, the Great Plains states of Idaho, Kansas and Montana, North Dakota, and South Dakota, plus California grow 67% of the crop (USDA, 1987). The main ecological factors limiting alfalfa distribution are winter temperature, water and diseases. It can be grown on virtually all soils. The majority of the crop is grown in rotation with corn and a small grain in sequences of 3 to 5 years length. Most alfalfa is fed to dairy or beef animals on the farm where it is grown or on neighboring farms. Some is shipped interstate as hay or as high density cubes or pellets.

Several other forage legumes, perennials and annuals, are important to U.S. agriculture, but not subject to statistical reporting by the U.S. Department of Agriculture. Like alfalfa, these legumes are primarily used as animal feed and are grown in rotations or in pasture. Perennial species such as red clover, birdsfoot trefoil, and vetches are occasionally substituted for alfalfa in Northern states. On some

midwestern farmland enrolled in the conservation reserve program, large areas are sown to hairy vetch or to sweet clover-alfalfa mixtures. In the south where alfalfa is poorly adapted, annual clovers such as white clover, arrowleaf clover, and crimson clover play significant roles.

Peanut is an annual legume used as a food source for humans and a fodder source for animals. It is adapted throughout the southern U.S., from Virginia and the Carolinas to New Mexico. The U.S. Department of Agriculture tabulated production statistics in 10 states; Georgia and Texas produce at least half the crop (USDA, 1987). The main ecological factors limiting distribution are water, temperature, and pests. Within its area of distribution, production of several market classes of peanut are subject to area restrictions by farm commodity programs. The crop is grown in rotation with small grains, vegetables, or coarse grains such as corn or sorghum depending upon the specific geographical area and farm enterprise.

Several market types of dry edible beans are produced for human food. Quality (appearance, taste) standards must be achieved for economical production. The highest quality dry beans are produced in growing seasons characterized by cool springs, warm summers with relatively low humidity, and dry falls. These characteristics lessen the impact of diseases that would discolor or rot the bean and reduce its quality. For these reasons dry bean production is restricted to some of the northern and Great Plains states, plus California. The crop cannot be economically grown in the humid parts of the U.S. The U.S. Department of Agriculture tabulates dry bean production statistics in 12 states; Michigan, North Dakota, California, Idaho, Colorado, and Nebraska produce at least 85% of the crop area (USDA, 1987). In the

areas of distribution, the crop is grown in rotation with corn or small grain.

Snap bean, an annual legume grown for processing for human food, must meet high quality standards (chiefly fruit appearance). The highest quality snap beans are produced in growing seasons with cool springs and summers. These temperature conditions are met by growing the crop successively from south to north as the growing season progresses. The growing season is restricted to avoid fungal, viral, and bacterial pathogens which attack the fruit and diminish market quality. The U.S. Department of Agriculture tabulates snap bean production statistics in 12 states from the south through middle Atlantic, upper midwest, and northwest. New York, Michigan, Wisconsin, and Oregon produce 70% of the crop area (USDA, 1987). In the areas of distribution, the crop is grown in rotation with small grains or corn.

Green pea is an annual legume grown for processing as human food. Like snap beans and dry edible beans, commodity quality is an important production goal. Temperature is the primary ecological factor governing quality, and for this reason the crop is primarily restricted to the northern tier of states. High growing season temperatures reduce pod set and seed yield, and favor pests that also reduce quality. Production statistics are tabulated on 7 states; Wisconsin, Washington, and Minnesota produce 68% of the crop area (USDA, 1987).

Several additional annual legume species are grown to produce special use commodities for various domestic and export markets. National statistics are unavailable for these crops. In the aggregate the area grown might equal that of snap beans for crops such as dry field peas, adzuki beans, lentil, and cowpea. The regional use of major

legumes in U.S. cropping or tillage systems is summarized in Table 2 (Heichel, 1987a).

Legumes derive N from three principal sources: through commercial fertilizer or manure application; by mineralization of indigenous soil organic matter; and by symbiotic N_2 fixation (Fig. 2). Hay and pasture legumes grown on a soil with the same initial N concentration in the profile derive different amounts of N_2 from symbiosis (Table 3). Birdsfoot trefoil may derive less N_2 from symbiosis than the other hay or pasture legumes because of its lower productivity and lack of persistent nodules, which must regenerate after each harvest. The amount of N_2 fixed also varies with growth stage (Table 3) and year of stand (Table 4), which may reflect the dynamic balance between the availability of soil N to the plant and the activity of the root nodules.

In addition to species, growth stage, and inherent soil fertility, legume N_2 fixation can be influenced by crop management practices, life form (annual or perennial habit), and location or environment. In general, and with one important exception, the environmental factors that promote high yields are conducive to high rates and high seasonal totals of N_2 fixation of legumes nodulated by effective bacteria. Such factors include: (1) optimum mineral nutrition at a pH slightly below neutrality, (2) a long growing season, (3) low concentration of plant-available soil N, (4) optimum water availability, and (5) freedom from insects or pathogens. High rates of N fertilization of legumes seldom significantly enhance yields, but nodulation and N_2 fixation are markedly reduced.

Selection of annual legume cultivars for rapid emergence after

planting, rapid leaf area expansion, high productivity, and maturation before the end of the growing season would favor highest N_2 fixation. Also, management practices and cultivar selection that enhance stand persistence would favor N_2 fixation of perennial legumes.

Although these principles can be listed, evidence to support each is inferential because field experiments on N_2 fixation per se are seldom performed in which cultivar, management, and environmental variables are not confounded. However, with improved methods of measuring N_2 fixation in the field, values representative of hay and pasture legumes (Table 5) and seed and pulse legumes (Table 6) grown in North American cropping systems can be summarized. These measurements were made using either of two procedures known to be the most accurate for determining the contribution of symbiotic N_2 fixation to the total N economy of a legume crop community: the difference method and the isotope dilution method (Henson and Heichel, 1984).

The values of N_2 fixation in the total crop (Tables 5 and 6) include only N_2 removed from the earth's atmosphere and sequestered within the plant; N derived from soil organic matter or from fertilizer sources has been excluded. Dinitrogen fixed by legumes can be viewed as a free resource because it occurs as a consequence of capture of the energy of continuously renewable sunlight in the photoassimilates of green plants. Substituting fixed legume N for fertilizer N results in production of economic plant products with less dependence upon commercial N fertilizers. However, a net enrichment or renewal of the soil resource by fixed N in legumes can only occur when the legume is grown and managed with attention to returning fixed N contained in above-ground plant material to the soil rather than permanently

exporting it from the land as hay or grain (Heichel, 1987a,b).

Legumes as N Sources in Cropping Systems

Legumes have long been known to improve the yield of subsequent nonlegume crops (Pieters, 1927). The role of N_2 fixation by legumes as one factor in this yield improvement became known early in this century (Fred et al., 1932) although other factors known as 'rotation contributions' have been implicated (Baldock et al., 1981; Heichel and Barnes, 1984; Hesterman et al., 1987). Use of legumes as green manures in U.S. cropping systems reached a maximum about 1940, when an estimated 13.0 million acres (3.5% of harvested cropland) were planted (Rogers and Giddens, 1957). The knowledge that forage legumes were capable of fixing N_2 frequently fostered the belief that practically all legume N was derived from the atmosphere, despite some pioneering evidence that soil N substituted for atmospheric N_2 in legume nutrition (Allos and Bartholomew, 1959). Thus, the N fertilizer replacement value of legumes in U.S. agriculture was commonly based upon the N content of the phytomass incorporated as a green manure (Stickler et al., 1959, Schmid et al., 1959), without regard to the possible uptake and recycling of soil N by legume.

The amount of legume-fixed N_2 made available to a nonlegume crop depends upon plant, environmental, edaphic, and management factors. For ease of discussion, I will consider two management situations. The first is an intercrop where the legume and nonlegume are grown concurrently. The second is a rotational sequence where the legume is grown and harvested, with legume residues being incorporated into the soil by some form of tillage to serve as a N source for a subsequent nonlegume crop.

Intercropping Systems. The inference that N is transferred from legumes to nonlegumes during intercropping (e.g. in legume-grass swards) has based on observations made in controlled and field environments (Heichel, 1987b). Increased use of N tracer methodology has expedited measurements of legume-nonlegume N transfer and has allowed some assessments of its significance in the field. Pot-grown ryegrass received 27% of its N from associated white clover over a 17-week period, while field-grown ryegrass on the same soil obtained less than 6% of its N from associated white clover (Haystead and Marriott, 1978). In another experiment, ryegrass obtained 12% of its N from associated white clover, with transfer occurring only at the fourth harvest of a 105-day season (Haystead and Marriott, 1979). In similar experiments ryegrass grown in the field obtained up to 80% of its N from associated ladino clover, but no transfer was observed in the glasshouse (Broadbent et al., 1982). Cereals obtained 15 to 30% of their N content from legumes in tropical intercropping systems (Eaglesham et al., 1981; Patra et al., 1986).

Recent field results from mixtures of reed canarygrass with alfalfa or with birdsfoot trefoil showed that 64% to 79% of the N in the grass was originally symbiotically fixed by the legume. This N represented 13% of the N_2 fixed by birdsfoot trefoil and 17% of that fixed by alfalfa. The results indicated that N transfer occurred over a distance of 8 inches, with maximum N transfer in areas of high legume/grass ratio (Brophy et al., 1987).

In all such N transfer experiments, the method(s) and mechanism(s) of transfer are unclear. Although direct excretion or degradation of nodule and root tissue are the usual explanations (Mulder et al., 1977),

no one has attempted to develop a budget to account for N transfer from various sources. Despite the emphasis on root and nodule degradation, other mechanisms may include stolon decay in some forage legumes, abscission of leaves and petioles in soybean-small grain intercrops, loss of leaves to pests or pathogens in other legume species, or death of individual legume plants within the intercrop or legume-nonlegume sward (Heichel, 1987b). Except for the emerging quantitative evidence on N transfer between forage legumes and grasses (Brophy et al., 1987), little is known of the quantity or significance of N transfer from legume to nonlegume in forage intercropping systems, or the ratio of legume to nonlegume needed to achieve significant transfer.

Rotational Cropping Systems. Rotations are cropping sequences in which crops are grown in specific order for a defined duration. In many crop rotations, nonlegumes are preceded by legumes so that the residual N from the legume might nourish the succeeding crop. By reflecting on the N sources available to legumes (Fig. 2), it should be apparent that several factors mediate whether the return of legume N to the soil represents a net input of symbiotically-fixed N potentially available to the crop or prone to other fates (Fig. 1), or merely a return of soil-derived N that was temporarily sequestered in the crop. The following discussion will exemplify that the N enrichment of the soil by legumes for eventual use or loss depends upon (a) the quantity of legume residues returned to the soil, (b) the content of symbiotically-fixed N in the residues, and (c) the timing of tillage operations and legume residue decomposition in relation to accumulation of symbiotically-fixed and soil N by the legume. The actual recovery of legume N by a succeeding crop, and the risk of legume N loss, will be considered in

Section IV.

Nitrogen budgets for soybeans developed from N tracer experiments (Heichel, 1987b) illustrate the partitioning of fixed N_2 in a crop with different amounts of symbiotic activity (Table 7). In the midwestern United States soybeans may fix 40% and obtain 60% of their N from the soil either from mineralization of organic matter or from carryover of fertilizer applied to a preceeding crop. When these crops are harvested for grain, soil N export in the harvested grain may exceed symbiotic N_2 return in the residue, which leads to a calculated soil N deficit of 74 pounds/acre N. If the same crop is grown under conditions where it fixes 90% of its N, for example, in the Piedmont region, the return of fixed N_2 in the residue may exceed soil N export in grain by 22 pounds/acre N.

Typically, only part of the symbiotically fixed N_2 in a hay or pasture legume is returned to the soil for use by a succeeding crop. This is because a portion of the fixed N_2 is removed from the land when the legume is harvested, with the balance remaining in unharvested roots and crowns. The N available for incorporation into the soil depends on the time of the season when incorporation occurs and the proportion of the plant that is N-rich herbage compared with relatively N-poor crown and roots. The N budget in Table 8 illustrates the net N return to the soil that is possible when alfalfa is incorporated by either fall or late-summer moldboard plowing (Heichel and Barnes, 1984). Comparable data for noninversion tillage practices are not available.

If two herbage harvests are taken, followed by herbage regrowth before moldboard plowing on October 20, the early season N deficit is nearly replaced by the late season N_2 fixation, with an inconsequential

loss of 4 pounds/acre N. A seasonal N deficit of 30 pounds/acre N would occur if a third herbage harvest was taken after the first frost, but before the October 20 tillage operation, so that only roots and crowns were incorporated. In contrast, removal of one herbage harvest followed by plowdown of a lush regrowth on August 30 allowed a net input of 48 pounds/acre N. Clearly, cutting management of the legume influences how much symbiotically-fixed N is eventually returned to the soil. In related experiments, tillage method had no consistent effect on the N or dry matter yield of sudangrass following alfalfa (Groya and Sheaffer, 1985).

In living mulch tillage systems forage legumes can be inhibited by sublethal applications, or destroyed by lethal applications, of herbicides before seeding of a subsequent crop with reduced tillage methods (Cardina and Hartwig, 1981; Elkins et al., 1983). In such situations, losses of volatile N compounds from decaying plant material undoubtedly occur, but the extent and significance of these losses to the N balance of the cropping system is poorly understood. Similarly, the yield stimulation of a nonlegume interseeded into a chemically suppressed living mulch has not been ascribed quantitatively to the transfer of soil N, symbiotically fixed N_2, or stimulation by some non-N factor. The results ascribing yield stimulation to N transfer (Elkins et al., 1983) are equivocal at best.

III. THE SOIL ENVIRONMENT

Legumes may return N to the soil, either N derived from the atmosphere by the process of symbiotic fixation, or that initially derived from the soil and stored in the crop until it is soil-incorporated by tillage or other processes. Whether the soil is

enriched or depleted of N by legume cropping depends upon how much N_2 the crop fixed, and how the crop was managed.

Growing legumes may elicit physical or biological changes in soils beyond those associated with the direct addition of N. These changes are sometimes interpreted as non-N rotation effects on the yield of following crops (Heichel and Barnes, 1984). Physical and biological changes in soils accompanying legume cropping conceivably may mediate the behavior of legume-derived N in soils. The theory and science of these phenomena are poorly understood. In this section several factors of the soil environment will be compared for cropping situations containing legumes (legume-based) and those containing crops nourished by fertilizer N(fertilizer N-based). The data base for this comparison is quite limited.

Legumes are often credited with improving soil tilth. Unfortunately, the tilth concept lacks a simple, operational definition. The historical concept of tilth is phrased as "open, free-working, mellow, or in good heart" (Fream, 1890). A contemporary statement (SSSA, 1984) regards tilth as "the physical condition of the soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration." Even the contemporary definition is debated (Karlen et al., 1989). Factors currently thought to mediate tilth include soil structure, soil aggregation, soil strength, soil organic matter (including flora and fauna), and soil aeration, as individually and collectively modified by cropping practices, tillage practices, and N management. These factors are not mutally exclusive, as the following discussion shows.

Soil aeration is a property of porosity, the proportion of a

defined soil volume occupied by pores rather than by solid particles. In practice, soil pores are filled with air, with water, or with a a mixture of the two. Soil porosity varies with cropping practices, and affects the metabolism of soil microorganisms. For example, soil cropped to oat undersown by clover had 50% air-filled soil pores and supported higher rates of microbial respiration than the same soil fertilizer N-based with about 58% air-filled pores (Doran et al., 1987). Tillage improves soil tilth in the short term by improving the balance between air-filled and water-filled pore space. In the long run it may reduce tilth by hastening the loss of organic matter by oxidation.

Organic matter has a strong influence on soil tilth; it encourages soil aggregation, water infiltration and storage, microorganism activity, and improves soil nutrient supply and productivity (Allison, 1973; Johnston, 1986). Legume-based cropping practices may result in higher soil organic matter content than fertilizer N-based practices (Reganold et al., 1987; Martyniuk and Wagner, 1978). However, this sometimes is not the case (Doran et al., 1987; Fraser et al., 1988). The most reasonable interpretation is that legume-based cropping systems will maintain an existing content of organic matter more readily than fertilizer N-based systems (MacRae and Mehuys, 1985). Whether accumulation occurs depends upon the interplay of at least 37 factors (MacRae and Mehuys, 1985), not the least of which is the time that the cropping system is in place.

Organic matter is an energy (carbon) and N source for soil microorganisms and arthropods. Thus, it is logical that cropping practices that foster organic matter accumulation may create a soil environment that supports high populations (Martyniuk and Wagner, 1978),

biomass (Doran et al., 1987) and activities (Fraser et al., 1988) of soil microorganisms. Red clover, a perennial forage legume, elicited higher contents of soil microbial biomass and metabolic activity than did soybean, an annual legume, or corn (Doran et al., 1987). The source of organic matter and its composition may be more important to soil microorganism activity than the species and life form (annual or perennial) of the legume in the cropping system.

The content of total N in soils cropped to legume-based versus fertilizer N-based systems is affected by the same factors that govern organic matter accumulation in soils (MacRae and Mehuys, 1985). In two comparisons (Doran et al., 1987; Fraser et al., 1988), the organic N pool was little influenced by crop rotation and cultivation practices. The changes in the physical environment (e.g. temperature, rainfall) and soil microorganism activity that affect mineralization of organic N are of greater importance to crop nutrition and ground water quality (Doran et al., 1987). Strategies with which to manage organic N mineralization in relation to rainfall and crop N demand are lacking.

A soil aggregate is 'a unit of soil structure formed by natural processes as opposed to artificial processes, and generally less than 10 mm in diameter' (SSSA, 1984). Except in very sandy soils, the formation and stabilization of soil aggregates is little influenced by organic matter (MacRae and Mehuys, 1985). In contrast, the decomposition products of organic matter are the primary stabilizing agents for aggregates. These products include microbial gums and mucilages, linear organic polymers like fats and waxes, fulvic acid, and soil polysaccharides (Greenland et al., 1962; Lynch, 1981; Molope et al., 1987). In two long-term studies, aggregation was greater in a crop

rotation incorporating a forage legume than with continuous corn (Wilson and Browning, 1945; Van Bavel and Schaller, 1950). A legume-based cropping system fostered greater accumulation of soil polysaccharides than did a fertilizer N-based system, but aggregation was not measured (Reganold et al., 1987).

Soil structure, i.e., the arrangement of soil aggregates and interconnected pore spaces in a characteristic pattern within a vertical section from the topsoil downward, varies with cropping system. For example, the modulus of rupture (a measure of the hardness of soil surface crusting) was significantly less for soils of a legume-based than for a fertilizer N-based cropping system (Reganold et al., 1987). Macropores, i.e., channels, formed by roots, earthworm activity, and the natural separations of soil structural units, are though to be deeper and more continuous beneath deeply-rooted perennial legume crops like alfalfa than beneath shallow-rooted crops (Russelle and Hargrove, 1989). Pore continuity is also influenced by tillage, regardless of cropping practices. Clearly, the aggregate and structural properties of soils grown to various crops might affect water movement and retention.

Cropping sequence influences water content of surface soils, on both a gravimetric and volumetric basis (MaeRae and Mehuys, 1985). The volumetric water content was significantly greater in the upper profile of soils from a legume-based than from a fertilizer N-based system (Doran et al., 1987; Reganold et al., 1987). However, the availability of soil water for plant growth, and not soil water content, is the major issue for crop productivity. The prevailing interpretation is that differences in soil texture and porosity have a greater effect on the availability of soil water to plants than organic matter differences

due to cropping sequence.

Cropping sequence influences water infiltration into soils (Fahad et al., 1982). Moreover, organic matter strongly affects water movement into soils (Wischmeier and Mannering, 1965). However, lack of specific comparisons between legume-based and fertilizer N-based cropping systems precludes conclusions about the influence of various legume species on soil water movement.

In summary, our conceptual understanding of the soil environment in legume-based versus fertilizer N-based cropping systems is in its infancy. However, knowledge of the individual physical and biological factors affecting the soil environment has increased multifold in the past century. This is best exemplified by the concept of 'tilth', which was defined in only seven words in 1890 (Fream, 1890) while a contemporary definition uses 63 (Karlen et al., 1989).

IV. LEGUMES AS NITROGEN SOURCES.

Legumes hold potential for supplying N to interplanted and succeeding crops. Not only do these crops accumulate substantial amounts of symbiotically-fixed N, but the timing of decomposition of these crops in relation to uptake by a succeeding crop may result in less N loss from the soil profile than from manufactured fertilizers. Thus, it is instructive to compare crop N recoveries from manufactured N fertilizers and from incorporated legume residues, and to assess the fate of the unrecovered N.

A complete review of fertilizer N use on grain crops is beyond the scope of the present assessment. Nevertheless, it is instructive to exemplify the fates of fertilizer N used on a major row crop, corn, to provide a framework against which to judge the use of legumes as N

sources.

The recovery of fertilizer N in the above ground portions of grain crops seldom exceeds 50% at recommended rates of fertilizer application (Fig. 3) and is often lower (Legg et al., 1979; Bock, 1984). The remaining N may be lost by volatilization, denitrification, immobilized as N-containing soil organic matter, stored as nitrate within the soil profile, lost to erosion, or leached to ground water. The partitioning of fertilizer N among these fates varies with edaphic, cultural, and management conditions, and is subject to much interpretation. Nevertheless, the losses of nitrate in tile drains in proportion to N fertilization rates in irrigated (Pratt, 1984) and rainfed agriculture (Gast et al., 1978) is compelling circumstantial evidence that fertilizer N escapes the root zone of growing crops. In irrigated crop production, the N losses ranged from 2 to 30% of that applied (for a mean loss of 50 lb/ N/acre/year) after correcting for N loss from unfertilized controls (Pratt, 1984). After 3 years of production of rainfed continuous corn, up to 27% of the applied N fertilizer was lost from tile drains; this was about 22 lb N/acre/year at the recommended rate of fertilization (Gast et al., 1978).

Replacement of Fertilizer N by Legume N

Grain crops like corn obtain some of their N needs from the uptake of N mineralized from soil organic matter. The amounts available from this source vary with the inherent fertility of the soil and with cultural practices. The crop usually requires supplemental N from fertilizer or from some other source to achieve a profitable yield. Although practices vary with region and with farm enterprise, corn may require about 110 lbs N/acre of supplemental fertilizer to maximize

profit under current midwest U.S. conditions. This recommendation for application is made with the knowledge that little more than about 50% of the applied N may be recovered in the harvested crop (Fig. 3) (Legg et al., 1979).

Can use of legumes as a supplemental N source for a crop like corn provide sufficient N for a profitable yield? Even more explicitly, can corn recover from incorporated legume residues amounts of N similar to those applied as supplemental manufactured fertilizer?

Upon initial encounter the question seems straight forward; simply plow down a legume, plant corn, and measure whether the corn yields match or exceed those obtained by replacing the legume by manufactured N fertilizer. This approach yields an interpretation known as the "fertilizer N replacement value" of a legume.

The fertilizer N replacement value (FRV) is a method to assess the N-supplying capability of a legume preceding a nonlegume. The values represent the amount of manufactured N fertilizer that would be required to produce a corn yield equivalent to that following a legume under otherwise comparable test conditions (Fribourg and Bartholomew, 1956; Higgs et al., 1976). Legumes so evaluated are interpreted as replacing various amounts of fertilizer N during the first nonlegume cropping season after legume plowdown (Tables 9,10). The values vary with location and species (Table 9). Within a location, FRV varies with legume species and crop management (Tables 10,11). For many tests, the FRV for perennial legumes like alfalfa are similar to the rates of fertilizer N recommended for corn. However, the FRV of soybean (Table 11) is small.

In short-rotation studies of legumes and nonlegumes (Table 10),

incorporation of alfalfa managed in a 1-cut system gave corn grain yields equal to those expected from 100 to 200 lbs N/acre from fertilizer. The incorporation of alfalfa managed in a three-cut management gave a corn grain yield response equal to the application of 50 lbs N/acre. Corn yields were greater with incorporation of more residual alfalfa N in the one-cut system compared to the three-cut system. However, corn yields following a non-N_2 fixing wheat crop were also greater than corn following corn (a FRV for wheat of about 25 lbs N/acre). Moreover, the FRV of wheat in rotation with corn in a 6 year study was 120 lbs N/acre (Langer and Randall, 1981). These results suggest that there are benefits of changing species in crop rotations that cannot be explained by legume N. These non-N "rotation effects" may account for 38 to 100% of the FRV (Hesterman et al., 1987; Russelle et al., 1987).

An example of an appropriate use of the FRV approach is to estimate a minimum amount of fertilizer N required by a nonlegume following a legume. One shortcoming of the approach is that the magnitude of the FRV estimated in a specific experiment depends strongly upon the efficiency of fertilizer N used achieved by the nonlegume. For a fertilizer N use efficiency of 50%, a 150 lb N/acre application would result in crop recovery of 75 lbs N/acre from fertilizer. A similar crop recovery of N and crop yield could also result from an application of 250 lb N/acre of fertilizer N and a fertilizer use efficiency of 30%. Experiments conducted under these two conditions would estimate a difference of 100 lbs N/acre in the FRV of the legume.

The FRV approach does not provide accurate assessment of the contribution of legume N to a succeeding crop owing to several

confounding issues. Use of the FRV to estimate legume N availability requires the following assumptions:

* The entire increased nonlegume yield is due to N; this clearly is not true.
* The N in the fertilizer source and in the legume residue are equally available.
* The N-supplying capacity of the soil is not altered in comparison to N fertilization by growing legumes and incorporating their residues.
* The response of the nonlegume crop to the N from the legume residue does not distinguish between the N fixed by symbiosis and the turnover of soil-derived N that comprises the balance of the legume N.

The method does not separate "new" N obtained from the air during legume growth from "old" N already in the soil and legume plants. Despite these practical and theoretical shortfalls, the most compelling evidence that the FRV method overestimates the ability of a legume to provide N to a succeeding crop comes from recent research on the use of stable isotopes to monitor recovery of N from legume residues.

Several recent experiments have taken advantage of the power of ^{15}N methodologies to measure the recovery by nonlegumes of ^{15}N from labeled residues of various legumes. Recent experiments in Australia (Table 12) indicated that the first crop of wheat grown after field incorporation of legume (medic) residues recovered an average of 23% of the legume N, while the second crop recovered an additional 4% (Ladd et al., 1981). These results are consistent with those of pot experiments with other legumes (Heichel, 1987b). Recent U.S. experiments with corn following

alfalfa (Table 13) confirm that recovery of total reduced N in the legume was 25% or less the first crop year after residue incorporation (Harris and Hesterman, 1987). For a typical fall plowdown of 100 lbs N/acre from alfalfa managed as hay, no more than 25 lb N/acre would be recovered by subsequent corn. If the alfalfa were managed as a green manure with 200 lb N/acre incorporated in the fall, no more than 50 lb N/acre would be recovered by subsequent corn (Heichel, 1987b). For these examples, the legume N recovered would represent 15 to 30% of the N accumulated in the grain plus stover of a 150 bu/acre corn crop (Barber and Olson, 1968).

The emerging evidence indicates tht the maximum recovery of legume N by a grain crop like corn is at worst only half that generally observed for fertilizer N (Heichel, 1987b). Of course, extrapolating this evidence to all crops and growing conditions is hazardous. Nevertheless the question emerges about the fate of the legume N not recovered by the succeeding crop. In arid regions soil organic N is a major storage pool (Ladd et al., 1981), but for humid and subhumid regions typical of the U.S., the partitioning of legume N among various sinks, or fates, is unclear.

Evidence for Appearance of Legume N in Ground Water

Nitrogen from legumes may appear in ground water during cultural conditions causing mineralization of the organic forms of plant N to nitrate in soil solution, and when precipitation or irrigation sufficiently exceeds evapotranspiration to allow water loss from the root zone. Nitrogen may be released form legumes by several mechanisms (Russelle and Hargrove, 1989). Nitrogenous compounds may be released directly from living roots or nodules into the rhizosphere (Brophy et

al., 1987; Lory et al., 1988). Hay harvest, grazing, or herbicide suppression may cause death of roots or nodules and N release into the soil. Tillage of legumes into soil, or lethal herbicide sprays before no-till planting of another crop, will terminate plant life and render organic N prone to mineralization to nitrate. Any of these situations in combination with a leaching event will increase the risk that legume N will appear in ground water (Russelle and Hargrove, 1989).

Although the circumstances that might allow the loss of legume N to ground water can be easily predicted, there is only meager experimental evidence for leaching of legume-derived N to ground water in U.S. cropping systems. The evidence that is available is limited in interpretation because the sources of nitrate lost from the root zones of legumes have not been unambiquously identified by origin, i.e., nitrate from living or from decomposing legumes, nitrate from mineralization of soil organic matter, nitrate from fertilizer, or nitrate from other origins. The limited current status of knowledge is easily exemplified.

The nitrate content of a 7-ft soil profile beneath an irrigated alfalfa stand in Colorado was 62 lb N/acre, 15% that of the 403 lb N/acre measured in a 7-ft profile beneath irrigated and N-fertilized corn and sugar beet crops (Stewart et al., 1967). The low rate of nitrate leaching from alfalfa, 22 lb N acre/year, was attributed to its lack of N fertilization and to a rooting pattern that allowed nitrate extraction from deeper in the profile than for other corps. Nitrate loss beneath alfalfa was the least of all systems studied and less than that of native grassland. Owens (1988) confirmed low concentrations of nitrate in water leaching from the root zones of alfalfa in lysimetric

investigations in Ohio.

Nitrate leaching below the root zone of alfalfa irrigated five to nine times and harvested three times for hay averaged 39 lb N/acre/year in Idaho (Robbins and Carter, 1980). During the first growing season following alfalfa, about 81 lb N/acre/year moved below the root zone of an unfertilized bean crop. In the second growing season following alfalfa, 20 lb N/acre moved beneath the root zone of unfertilized bean and wheat crops. The average annual leaching of irrigation water through these profiles, 20 in/acre, represented excessive water application (Robbins and Carter, 1980). Although more prudent water management would have reduced nitrate loss, this example does illustrate that nitrate leaching from the root zone of extant alfalfa and from an unfertilized crop following alfalfa can occur in irrigated cropping systems.

Despite the paucity of experimental data on the leaching of legume-derived N in U.S. cropping systems, climate and crop production information can be used to suggest where the likelihood of legume N leaching losses may be greatest. As one example for a major legume, Peterson and Russelle (1989) analyzed where leaching losses from alfalfa might be most likely with occurrence of conducive climate and production conditions (Fig. 4).

Unfrozen soils cropped to alfalfa are capable of free drainage (leaching) when the soil profile is at or above field capacity for water for the part of the season when the crop is either actively growing or has been terminated by tillage. Following on Thronthwaite (1948), these soils are in the moist subhumid or wetter climatic zones (Fig. 4). The source of legume N is greatest in regions of greatest production (Fig.

4), as discussed above in Section II.

Peterson and Russelle (1989) believe that the likelihood of N leaching losses from alfalfa would occur at the intersection of the subhumid or wetter climatic zone with that of greatest alfalfa production (Fig. 4, crosshatched area). Except for irrigated alfalfa in the Central Valley of California, in southern Idaho, and in northeastern Colorado, the area most susceptible to leaching loss mirrors the U.S. corn belt. This is also the area for which no published data on legume N leaching losses are available.

Because of the paucity of data on N leaching associated with specific N release mechanisms from U.S. crops, estimates of legume N leaching over relatively long growing periods for legume crops grown in other nations were examined. This perspective was adopted since long periods of crop growth allow for the occurrence of many of the cultural or management events that may facilitate leaching of legume-derived nitrate.

Results of recent experiments conducted over a period of 6 years in lysimeters in Germany (Jung et al., 1989) indicated nitrate leaching losses averaging 26 lb N/acre/year beneath alfalfa and red clover. These losses occurred on loamy sand and sandy loam soils in a region where 8 of the 20 in of annual precipitation leached from the root zone. The annual leaching loss from the forage legumes was similar to that from a 2-year rye-corn sequence fertilized with a total of 178 lb N/acre. The greatest leaching from alfalfa and red clover occurred after plowing of legume residues into the soil, when N uptake by the succeeding crop was low, or when plant cover was absent from the soil. These experiments were conducted without the use of ^{15}N labeling

techniques, which would have aided in establishing the soil versus plant origin of the leached N.

In three Australian experiments in which rainfall ranged from 17 to 27 in. during a 1.25 year residue decomposition and wheat cropping period, 72 to 78% of the added legume ^{15}N was stored in soil organic matter (Ladd et al., 1981). Leaching was thought to be minimal because of the amounts and distribution of precipitation. Had leaching occurred, the maximum loss of legume N below the root zone would have been about 6 lb ^{15}N/acre/year or about 11% of the legume N applied (Ladd et al., 1981).

Legume N leaching experiments were conducted with non-isotopic methods, viz. soil nitrate samples, supplemental N fertilization, rainfall events, crop nitrogen recovery, and soil moisture content over 4 years at a site in New Zealand with about 26 in. annual rainfall (Adams and Pattinson, 1985). About 9 lb N/acre/year leached below the root zone of an established white clover stand in the first year of the 4 year white clover-pea-wheat-wheat/clover rotation. Following incorporation of the white clover, 80 lb N/acre/year leached below the root zone in the pea phase of the rotation. About 53 lb N/acre leached during the wheat year, and 31 lb N/acre/year during the wheat/clover year. Thus, an average of 43 lb N/acre/year leached below the root zone of this legume-based rotation. The leaching amounts may be overestimates for two reasons; possible denitrification losses were acknowledged by the investigators, and the leaching of legume N was not distinguished from the leaching of N mineralized from the soil organic matter pool.

Leaching of ^{15}N derived from mineralization of ^{15}N labeled

subterranean clover residues was compared with that from ammonium sulfate and potassium nitrate, two common fertilizer N formulations, in laboratory experiments in Finland using uncropped lysimeters (Muller, 1987). During the 75 day experiment, 75% of the clover N was mineralized. About 17% of the clover N (approx. 10 lbs N/acre), 50% of the ammonium N, and 70% of the nitrate-N was leached through the soil column by 9 in. of drainage from applied irrigation. In a subsequent field experiment conducted in a lysimeter cropped to barley, 65% of the clover N was mineralized, but only 1.4 lb N/acre/year (2% of the 70 lb N/acre applied) was leached from the lysimeter by 9 of the 26 in. annual precipitation.

Nitrogen losses to leaching were measured in a 4-year study of four cropping systems in Sweden, one legume-based, two fertilizer N-based, and one unfertilized (Long and Hall, 1987). Leaching losses were 16 lb N/acre/year for fertilized barley (15% of fertilizer N input), 1 lb acre/year for fertilized meadow fescue (0.5% of fertilized N input), 9 lb/acre/year for unfertilized barley (presumably from mineralization of soil organic matter), and 9 lb/acre/year (3% of symbiotic N_2 fixation) for alfalfa in which 64% of the N input was harvested as hay.

Comparisons of N leaching losses from legume-based with fertilizer N-based cropping systems must be cautious since few properly designed experiments exist to allow definitive attribution of N source (legumes, fertilizer, or soil organic matter) and rigorous interpretation. Accepting this strong scientific reservation, the foregoing discussion illustrated that fertilizer N leaching losses may range from 22 lbs N/acre/year (up to 27% of applied fertilizer N) in a rainfed, fertilizer N-based system to 50 lbs N/acre/year (up to 30% of applied fertilizer N)

in an irrigated, fertilizer N-based system (Gast et al., 1978; Pratt, 1984).

Like the leaching of fertilizer N, leaching of N from legume residues varies with amount and distribution of precipitation and irrigation. In the limited number of experiments where irrigation or precipitation were measured and ^{15}N-labeled residues employed, leaching of N from legume residues ranged from 1 to 9 lb N/acre/year, or about 2 to 11% of the legume N applied (Ladd et al., 1981; Muller, 1987). To a first approximation, the leaching losses of N from legume residues may be as little as 2% those of fertilizer N and as much as 41%. The losses may be no more than those observed from unfertilized cropping systems or native grassland in which the N source is mineralization of the soil organic matter (Stewart et al., 1967; Long and Hall, 1987).

V. FACTORS GOVERNING LEGUME USE AS A N SOURCE.

Legumes have several attributes that are useful in resource stewardship, in addition to their acknowledged nutritional characteristics. Legumes can access atmospheric N_2 for their own nutritional needs, a trait that cereal grain crops lack. Properly managed legumes can facilitate a net increase in N in the soil-plant system, beyond the normally small amounts of soil N that legumes feed upon and store. Desirable changes in soil physical and chemical properties may accompany legume growth. The atmospheric N_2 fixed by legumes may become available for use by intercrops or succeeding crops in rotation, thus displacing fertilizer N and conserving energy resources. Because N from legumes is initially in a form less available to plant roots than is fertilizer N, more legume N is retained in the soil organic matter pool. Consequently, the potential for loss of legume N

to ground water appears to be less than the potential for loss of fertilizer N. Accepting that legumes will seldom provide the total N nourishment needed by succeeding grain crops, several factors nonetheless bear on future use of legumes in cropping systems.

Biological Factors

Some legumes might be more widely grown than they currently are. Among the major legumes discussed in Section II, alfalfa is the most widely adapted and has the fewest biological restrictions on greater use. Soybean and the annual clovers are less widely adapted than alfalfa, but have potential for greater use within their regions of adaptation.

Among the three listed species, the availability of cultivars adapted to growth in specific regions, environments, and cropping systems (or the lack of germplasm from which to develop adapted cultivars) would limit significant expansion of these crops in the next 5 years beyond the areas where they are now grown. With sufficient program enhancement, legumes could be more widely grown in 10 years. The situation is particularly acute for legume cultivars adapted for use in reduced- or conservation tillage systems (Knight, 1987).

Increasing the capability of legumes to fix more N_2 is a formidable challenge (Heichel et al., 1989). A special purpose alfalfa cultivar was released for use as a hay and plowdown N source in a 2-year rotation with corn (Barnes et al., 1988). This cultivar achieved a greater N_2 fixation capacity primarily by an extended growth period, but it may prove to be a model for increasing the usefulness and adaptation of other crop legumes.

Social and Economic Factors

Legumes are currently grown in a variety of farm enterprises because they facilitate achieving enterprise (not just single crop) profitability. This is accomplished by use of the legume as a cash crop (e.g., soybean and vegetable legumes) or as an animal feed (e.g., alfalfa and clovers) on the farm where it is grown or on another farm in the same locality. The cash market for forage legume hay or other products is small. However, the hay market will grow as the traditional techniques of measuring hay quality, chiefly physical and organoleptic methods devised by humans, are replaced by wet chemical and infrared spectroscopic procedures which attempt to aggregate all nutritional attributes of hay in one index known as relative feed value (Rohweder et al., 1981; Linn et al., 1987). In this way hay and hay products from different regions with similar nutritive value to animals can be equitably marketed without the necessity for on-site inspection by the buyer. Grading standards for feed grains achieve the same purpose.

Some legumes are grown almost entirely for specialty markets. Vegetable legumes (beans, peas, peanut) for human consumption are obvious examples. Adzuki bean is grown on limited acreage in Minnesota and North Dakota for export to Japan for specialty food use. Soybean cultivars have been developed to meet a specialty market for human food. Even alfalfa is grown as a source of sprouts for human food. When legumes are grown for human food, product quality is the primary market consideration and will limit (e.g., peas, snap beans) the geographical area in which the crop can be profitably grown.

Because legumes have an acknowledged role in resource stewardship, their use in cropping systems is also subject to the values or ethics of

the producer. Some producers subscribe to low-input sustainable agriculture, organic farming, or resource preservation concepts that lead them to grow legumes alone or in rotations with other crops to provide types of N nutrition and pest control that do not rely up manufactured fertilizers or agricultural chemicals. To enhance profitability, these enterprises often target their commodities to consumer groups in the U.S. or abroad that prefer animal and plant products raised without certain types of chemicals. Some states have regulatory programs to monitor the market compliance of such commodites.

Access to markets is one socio-economic factor mediating a voluntary acreage expansion for a major- or minor-use legume. If the traditional markets of animal feed or human food are not viable, policies might be considered to promote alternate uses. Oilseed crops as a source of chemical feedstocks or portable fuels, and legume hay as an energy feedstock for direct combustion in power plants are familiar examples for which policy and economic factors have been analyzed (OTA, 1980).

However, the major economic factor limiting the diversification of farming enterprises to include rotations incorporating legumes is the current commodity programs. Under current commodity program regulations, producers must maintain a base acreage of program-supported crops (e.g., corn, wheat) to qualify for maximum subsidy payments on these crops in the future. The commodity program regulations prevent the use of crop rotations containing legumes in regions where the rotation could be an economic alternative for the farmer or an environmental benefit to society. Thus, the commodity programs penalize farmers who choose to adopt rotations containing non-program crops.

VI. INTERPRETIVE DISCUSSION

It is impossible to advance a prescription to prevent nitrate leaching from soils to ground water. This is because nitrate, mineralized from soil organic matter and dissolved in water, leaches from the root zone of unfertilized grasslands and agricultural fields. Leaching is a natural pathway within the N cycle. Nitrate is a naturally-occurring form of N in all bodies of water, not a contaminant of synthetic or xenobiotic origin.

The concentration of nitrate in ground water, the issue upon which public policy focuses, is controlled in the simplest scenario by either of two factors: the rate of nitrate addition to a constant flow of water, or the rate of water flow through a region where nitrate is steadily becoming available. The nitrate concentration in the water contained in unfertilized soils of grasslands and fields is often negligible, but may reach 3 ppm; it varies with rate of nitrate mineralization from native soil organic matter and with rate of water percolation through the soil. Nitrate concentrations in ground water are disconcertingly ephemeral; they vary with amount and timing of rainfall, edaphic factors, time of year, management of vegetation, and with the perplexing spatial variability of soils. Measurements of nitrate concentration in water provide little understanding of the nitrate loss from a specific area of soil or crop.

For these reasons and more, it may be useful to visualize nitrate losses from agricultural cropland as integrated fluxes, i.e., rate of nitrate movement from the root zone per land area per time. Reckoned in this manner, unfertilized native grasslands and agricultural fields lose about 20 lbs N/acre/year (range 5 to 40) as nitrate. This rate of

loss in a natural pathway in the N cycle is one that cannot be eliminated in the foreseeable future and might be considered as a policy target for a best management practice.

How closely do nitrate fluxes through cropland approach this proposed target? An exhaustive analysis of nitrate loss from fertilized cropland was beyond the scope of this document, but the brief illustrations in Section IV indicated that rainfed, fertilizer N-based crops lost an average of 22 and irrigated, fertilizer N-based crops an average of 50 lbs N/acre/year. Values half to twice these averages would represent the normal range of variation. The nitrate losses from rainfed, fertilized crops were similar to those of the proposed target, but those from the irrigated, fertilized crops exceeded the target by an average of 150%.

Nitrate losses from the rooting zone of living, irrigated alfalfa stands ranged from 22 to 39 lb N/acre/year. Studies on rainfed alfalfa and red clover stands, where up to 40% of the annual precipitation percolated through the soil, indicated nitrate losses of 9 to 26 lb N/acre/year. For these systems, the loss of nitrate was probably overestimated since the amount originating from soil organic matter was not accounted for. Nitrate losses beneath stands of irrigated alfalfa exceeded the proposed target by about 100% when excess water was applied. Losses of nitrate beneath rainfed alfalfa crops were either less than or similar to those from rainfed, fertilizer N-based crops.

Nitrate losses from root zones of unfertilized crops succeeding alfalfa may be substantial both in rainfed and irrigated situations. About 37 lb N/acre/year as nitrate (180% of the proposed target) was lost from rainfed wheat in the first year after incorporation of an

alfalfa stand. About 81 lb N/acre/year as nitrate (300% of the proposed target) moved below the root zone of an irrigated, unfertilized, and presumably symbiotically dependent bean crop in the first year after incorporation of an alfalfa stand. For these situations nothing is known about the pattern of mineralization of N from alfalfa residues in relation to the nutritional needs of the succeeding wheat or bean crops. The scope for synchronization of residue N release and crop N uptake is poorly understood. When the subsequent crop is a legume capable of N_2 fixation, the potential for uptake of N released from legume residues may be small. Alternating different legume species in rotation may be inadvisable because of the potential for nitrate loss from the profile.

Use of sensitive stable isotope tracer methods allows the origin of nitrate leaching from the root zone of a plant-soil system to be clearly identified. The amount originating from plants can be distinguished from soil sources. Data on loss of label from living stands of legumes have not been published; whether such experiments are underway is unknown. Experiments to determine leaching of labeled N from legume residues at U.S. sites are underway (personal communication). At this writing the few data published are from Finnish and Australian sources. These limited results indicate that nitrate losses to ground water from decomposing legume residues range from 1 to 9 lb N/acre/year, well below the target loss proposed.

Are generalizations from these very limited observations useful to suggest policies on use of legumes in crop rotations to lessen the risk of N movement to ground water?

Scientists would be hesitant to suggest policies because of the scarcity of data; they would propose more research to bolster the

knowledge base and avert the risk of grounding policy on minimum facts. The lack of knowledge is especially troublesome for:

* the rates of nitrate leaching beneath native grasslands and unfertilized agricultural fields,
* the rates of nitrate leaching beneath living stands of major crop legumes,
* the ability of deeply rooted legumes like alfalfa, and deeply rooted forage grasses, to remove nitrate that has leached deeply into the profile,
* the rate of release of nitrate from residues of legume stands destroyed by tillage or other management practices, especially during times of heavy precipitation in fall, winter or spring before a succeeding crop is planted,
* The rate of release of nitrate from residues of legume stands destroyed for planting to a subsequent crop, specifically the synchronization of nitrate release with nitrate uptake by the subsequent crop, and
* irrigation management strategies to avert the loss of nitrate from living and destroyed stands of legumes.

Policymakers might sense the trends of knowledge and, despite obvious limitations, attempt to identify policies to encourage modification of agricultural management practices at lesser public expense today than tomorrow; the price of inaction may be excessive. What knowledge trends are emerging?

First, nitrate loss to ground water occurs from the root zones of native grasslands and unfertilized agricultural soils. These natural or background rates of nitrate leaching provide a benchmark against which

to compare rates of nitrate loss from root zones of various agricultural crops.

Next, the limited data indicate that nitrate losses from root zones of living stands of rainfed forage legumes are no greater than those from living stands of fertilized nonlegumes or from unfertilized native grasslands and agricultural fields. Indeed, the nitrate losses may often be less. Thus, rotations based on forage legumes pose no risk to ground water beyond the normal nitrate loss from unfertilized fields. Moreover, living stands of forage legumes may extract nitrate leached deeply into soil profiles and prevent its loss to ground water.

The limited data indicate that nitrate leached from legume residues during the crop year following stand destruction by tillage may exceed by 100% or more that leached from unfertilized grasslands or agricultural fields. This occurs both in rainfed and irrigated systems and is attributable to (1) inadequate plant cover on soil following destruction of the legume stand, (2) lack of synchronization of N release from legume residues and N uptake by the succeeding crop, and (3) excessive percolation of water through the profile during non-cropped periods or when N uptake by a succeeding crop is slow.

Finally, whatever the desirability of using legume-based cropping systems to minimize the risk of nitrate leaching to ground water, current commodity support programs discourage or preclude their adoption. This is because of the necessity for producers to maintain base acres of supported crops to qualify for the commodity programs. The need to couple commodity support and water quality policy is evident.

VII. POTENTIAL CONGRESSIONAL POLICY OPTIONS

Using legumes as a N source in cropping systems may have beneficial consequences to ground water quality and facilitate reaching other environmental stewardship goals. Because N management decisions are made on an enterprise (farm) basis, the individual farm enterprise is the best place to start when crafting policies to encourage or mandate the conversion from a contemporary N use practice to one posing less risk to ground water. Direct subsidies, tax credits, low interest loans, rezoning, direct buyout, condemnation, coupling or cross-compliance, or combinations thereof are among the instruments that might be used. Whatever policy is adopted, procedures for compliance will have to emerge one farm at a time and will probably differ greatly even among neighboring farms because of the site specificity of N use decisions. The sod- and swamp-buster, and conservation compliance components of the 1985 Farm Bill are useful models to emulate.

Some possible policy approaches are to:

(1) Adopt a logical target for annualized rates of nitrate loss from cropping systems to ground water. Advance a benchmark no more strigent than the annual rates of nitrate loss to ground water from native grassland and unfertilized agricultural fields. The initial target rates of nitrate loss should be established by major cropping region, then verified and refined by a focused research thrust (see 7).

(2) Craft complementary commodity support and water quality policies. The current commodity support program regulations (Food Security Act of 1985) inhibit the use of crop rotations containing forage legumes in regions where they would be an

environmental benefit to society, or an economic alternative for the farmer. Consider incentives in commodity support and crop insurance programs for adoption of legume-based crop rotations. Consider tax incentives for adoption of legume-based crop rotations.

(3) Mandate adoption on a regional basis over a period of 5 years of cropping systems with annualized nitrate loss characteristics not exceeding a benchmark value similar to that of native grassland and unfertilized agricultural fields. Charge federal regulatory and research agencies with developing the means to ensure availability of technology, implementation of methods, and compliance.

(4) Require producers of 'monoculture' nonlegume (e.g., grain) crops to adopt legume-based rotations to qualify for taxpayer subsidized benefits from all farm programs (including farm credit). The specific rotation chosen by the producer would depend upon the crop-animal-resource mix that fosters a profitable individual enterprise. This policy might lead to a shift in cropping patterns and enterprise diversification if animals are required to consume part or all of the legumes. This approach would be least feasible in the Great Plains, where deeply-rooted legumes grown in dryland conditions may exhaust soil water in the profile and reduce the productivity of a succeeding wheat crop.

(5) Require producers with a history of legume usage in their enterprise (a 'base' of legume use) to incorporate more (probably a percentage above the base) legume crops into the

enterprise to qualify for taxpayer subsidized benefits from farm programs. As in (4), the legume species chosen would depend upon the resource mix that fosters a profitable individual enterprise.

(6) Facilitate adoption of legume-based crop rotations in (2)-(5) with "rotation insurance." This will ease the social inertia to adoption and provide a mechanism for dealing with the possibility of reduced yields of grain crops grown in rotation with legumes. Producers who adopt a legume-based rotation and obtain reduced yields on subsequent non-legume grain crops would be able to apply for deficiency payments based upon the difference between grain yields in the rotation and the rolling 5-year average of grain yields grown on their farm in a fertilizer-N based system. As an added incentive, credit a proportion of the legume to base acres when it is rotated with an eligible crop. Funds for the insurance program could be obtained from a small tax on manufactured N fertilizers. Since society is the ultimate beneficiary of improved environmental quality, an alternate approach is to fund the program from general tax revenues.

(7) Redirect and refocus some research in USDA-ARS to ensure the investigation of the fate of fertilizer and legume N at a network of geographical sites that may be vunerable to ground water contamination. Specifically focus on obtaining complete N balances at all sites in the network, with fertilizer N-based, legume N-based, and unfertilized cropping systems. This research effort would directly support (1). Develop a

repertoire of methodologies for application at all sites in the network. Assure the collection of a common base of knowledge of accepted scientific quality throughout the network to augment research being conducted to solve site-specific problems. Assure that the new research undertaken complements that of the U.S. Geological Survey, the U.S. Environmental Protection Agency, other USDA agencies, and other federal institutions. Fund the new research with a small tax on manufactured N fertilizers. Since society is the ultimate beneficiary of improved environmental quality, an alternate approach is to fund the program from general tax revenues.

(8) Direct the execution of research targeted at conceiving strategies to mitigate potential losses of nitrate from legume N-based cropping systems to ground water. Focus on: nitrate leaching beneath native grasslands and unfertilized fields; nitrate leaching beneath living legume stands; extraction of nitrate leached deeply into profiles by use of deeply rooted crops; leaching of nitrate from destroyed legume stands in the absence of a subsequent crop, and its possible amelioration by nonlegume cover crops; synchronizing release of nitrate from destroyed legume stands with nitrate demand by a subsequent crop; mixtures or intercrops of legumes and nonlegumes to minimize leachable nitrate in soil solution; and managing irrigation water to minimize the risk of nitrate leaching from living and destroyed stands of legumes.

Any policies anticipated should consider the commodity markets open to restructured farm enterprises, market quality requirements of new

products, and possible displacement of farm families from enterprises of marginal financial health. Moreover, policies should anticipate the change in demand for some farm inputs that may occur with increasing adoption of legumes. For example, a policy that fosters a rapid conversion to legume-based rotations might cause the demand for certain types of forage legume seed (alfalfa, clover, trefoil) to exceed the supply. This situation was experienced during implementation of the Conservation Reserve Program, and led to seed shortage and high seed prices. With 2 years lead time, the farm seed industry could more easily cope with a greatly increased demand. Other farming inputs might be similarly affected by policies fostering adoption of legume-based rotations.

In conclusion, the present understanding of legume N assimilation, managing of living legume stands, managing nonlegume crops antecedent to destroyed legume stands, and substituting legume N for N from manufactured fertilizers, offers new challenges for research and for public policies to jointly address environmental stewardship issues. The outcome may be cropping systems that appeal to interests of environmental and economic sustainability, and complementary commodity support and environmental quality policies. Agricultural policy interests and agricultural research institutions have seldom confronted such rewarding, yet mutually beneficial, opportunities.

GLOSSARY

Cropping sequence: the annual pattern and spatial arrangement of crops or crops and fallow on a given area of farmland.

Cropping system: the sequence of crops used on a farm as affected by the physical resources, technology, and management skill available in the enterprise.

Legume-based cropping system: a cropping system in which legumes are the source of nitrogen for nonlegume crops.

Fertilizer-N-based cropping system: a cropping system in which commercially-manufactured fertilizer is the source of nitrogen for nonlegume crops.

Isotope dilution method: a technique for estimation of the N_2 fixation of legumes from measurement of the quotient of ^{15}N concentration in tissue of N_2-fixing legume and a non-fixing control. The dilution of ^{15}N by atmospheric ^{14}N in tissue of the fixing crop compared to that in the non-fixing control is directly proportional to the amount of N_2 fixed.

Difference method: a technique for estimation of N_2 fixation as the difference in accumulation of total reduced N between a N_2-fixing legume and a non-fixing control soley dependent upon soil N and similar to the test species in seasonal growth characteristics.

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Figure Legends

Fig. 1. The nitrogen cycle (Reeder and Sabey, 1987)

Fig. 2. Three regimes for N nutrition of Legumes. The left panel represents a regime in which all crop N is derived from the soil and move from symbiotic N_2 fixation. The right panel represents a regime in which the crop growing on N-impoverished soil is soley dependant upon symbiotic N_2 fixation. The center panel represents the typical midwestern regime with alfalfa obtaining N from both soil and symbiotic N_2 fixation (Sheaffer et al., 1989).

Fig. 3. Recovery of fertilizer N by corn grown after conventional and no-tillage (Legg et al., 1979).

Fig. 4. Areas of greatest likelihood of legume N leaching losses from alfalfa (Peterson and Russelle, 1989). Soils capable of free drainage were identified in the moist subhumid or wetter zones after Thornthwaite (1948). The major alfalfa production zones are taken from the Oxford Regional Economic Atlas (Chapman and Sherman, 1975).

Fig. 1

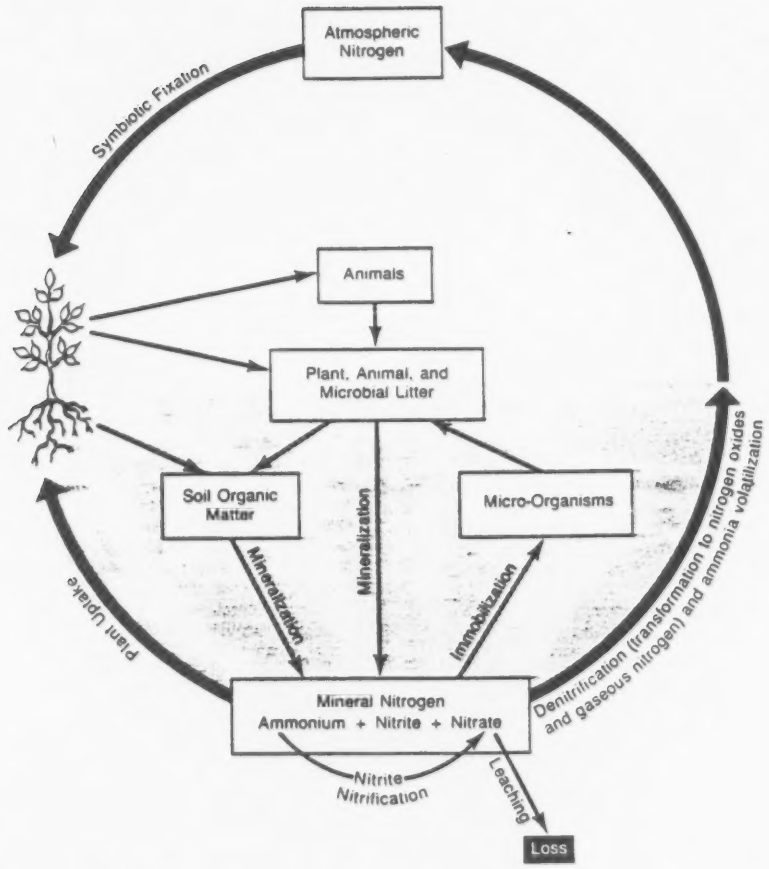
Atmospheric Nitrogen
Symbiotic Fixation
Animals
Plant, Animal, and Microbial Litter
Soil Organic Matter
Micro-Organisms
Mineralization
Mineralization
Immobilization
Plant Uptake
Denitrification (transformation to nitrogen oxides and gaseous nitrogen) and ammonia volatilization
Mineral Nitrogen
Ammonium + Nitrite + Nitrate
Nitrite
Nitrification
Leaching
Loss

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Fig. 2

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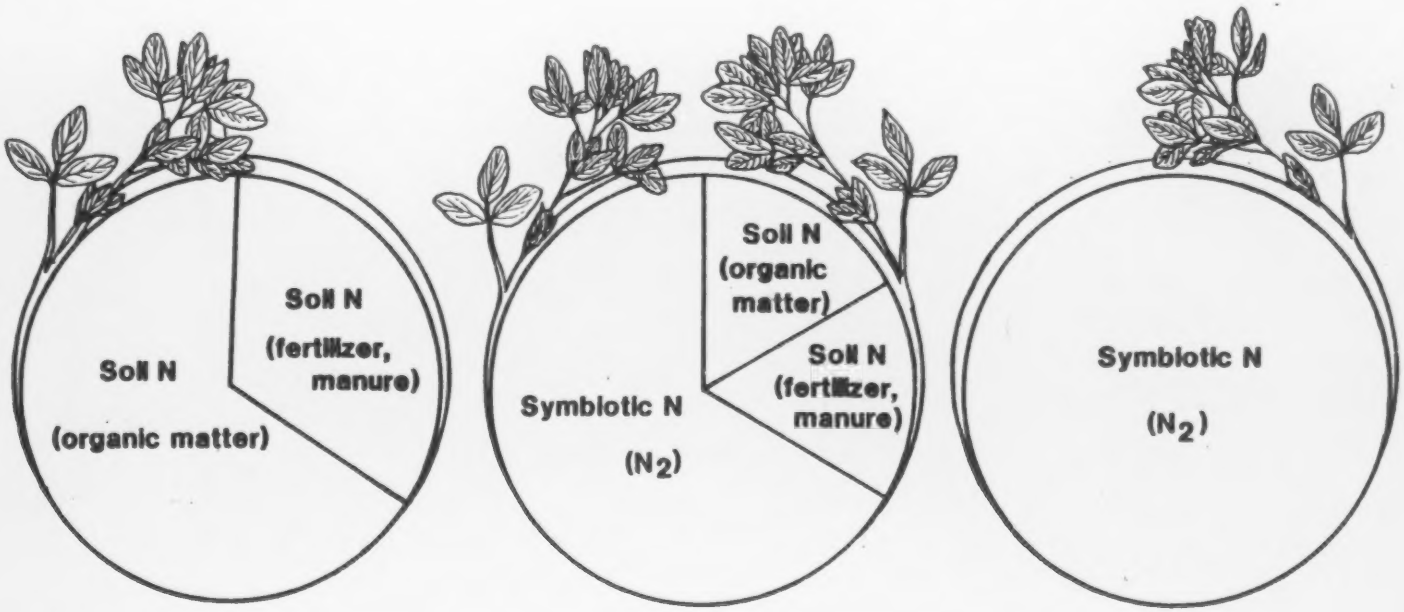
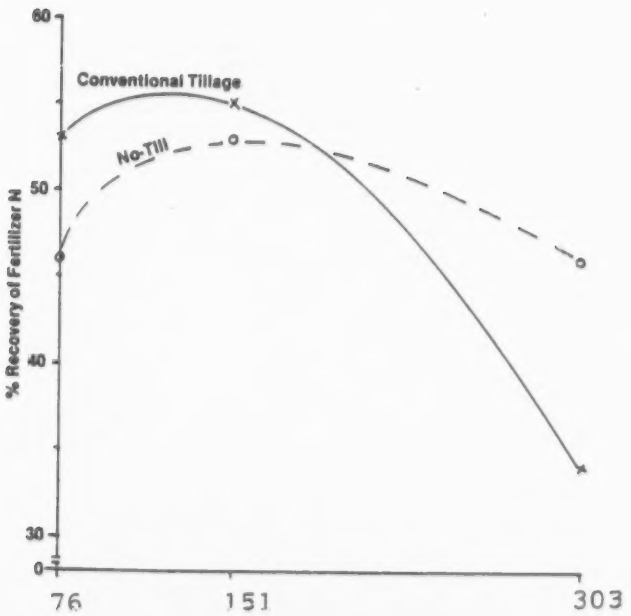

Soil N
(organic matter)
Soil N
(fertilizer, manure)
Symbiotic N
(N_2)
Soil N
(organic matter)
Soil N
(fertilizer, manure)
Symbiotic N
(N_2)

Fig. 3



Recovery of fertilizer N by no-till and conventionally grown corn.

Fig. 4

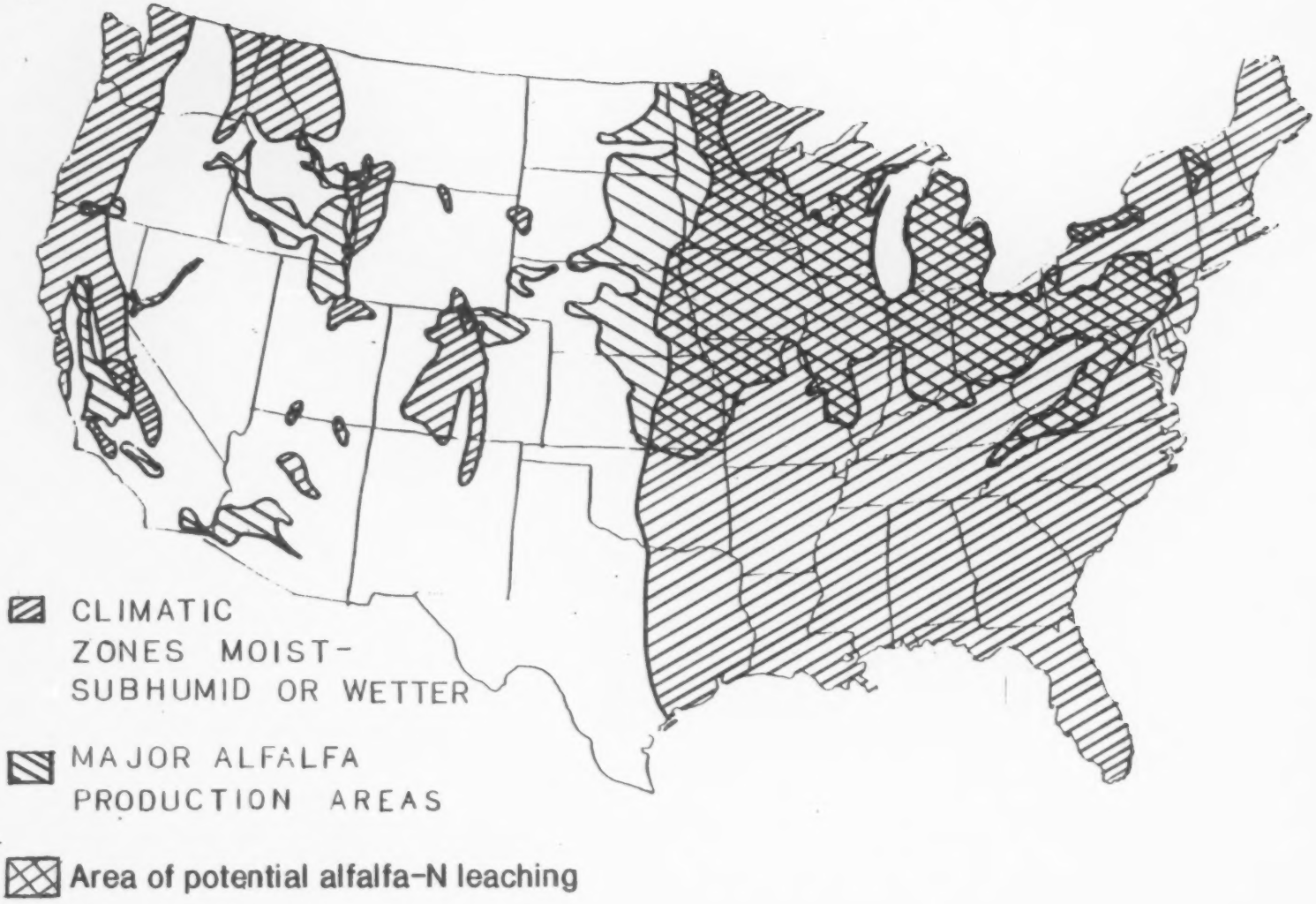

CLIMATIC ZONES MOIST-SUBHUMID OR WETTER
MAJOR ALFALFA PRODUCTION AREAS
Area of potential alfalfa-N leaching

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Table 1. Area harvested and value of major U.S. food and feed legumes, 1986.

Crop	Area Harvested	Value of Production
	10^3 acres	10^6 $
Soybean	59,416	9,326
Alfalfa + alfalfa mixtures	26,748	5,495
Peanut	1,536	1,065
Beans, dry edible	1,494	431
Peas, green	272	94
Beans, snap	190	97

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Table 2. Examples of regional use of legumes in cropping or tillage systems (Heichel, 1987a).

REGION	LEGUME SPECIES	CROPPING OR TILLAGE SYSTEM
Southeast	Crimson clover, hairy vetch	Winter cover crop, no-till corn. Crimson grazed during winter.
	Bigflower vetch, crownvetch, alfalfa, lupine, arrowleaf clover, red clover	Winter cover crops preceding grain sorghum and cotton.
Northeast	Alfalfa, birdsfoot trefoil, red clover	Legumes grown for hay or silage in crop rotations that include conventional or no-till corn as feed grain or silage; also used as living mulches.
North Central	Soybean, pea	Grown in 1-year rotation with nonlegume, possibly using conservation tillage methods; peas may precede soybeans in a double-cropping system.
	Alfalfa, red clover, white clover, alsike clover	Grown for 2 years or more in 3- to 5-year rotations with small grains or corn, possibly by use of conservation tillage methods.
	Birdsfoot trefoil	Grazing, forage.
	Crownvetch	Roadside stabilization, green manure.
	Sweet clover	Green manure; honey production.
	Hairy vetch	Winter cover crop.
Great Plains	Native legumes	Rangeland for grazing.
	Alfalfa	Grown under irrigation in rotation with beans, wheat, corn.
Pacific Northwest	Dry pea, lentil, chickpea	Rotation or double-cropped with grains.
	Austrian winter pea	Green manure or alternated with winter wheat.
	Alfalfa	Grown in rotation with winter wheat, spring barley, and winter peas.
	Faba bean	Grown in rotation for silage.
California	Dry bean, lima bean, blackeye pea, chickpea	Grown for grains in various rotations.
	Alfalfa	Grown for seed on irrigated land and for erosion control and forage on steeply sloping soils.
	Subterranean clover	Rangeland for grazing

Table 3. Variation of dinitrogen fixation capacity with legume species, legume productivity, and initial soil nitrogen concentration (Heichel, 1987a).

Species	N from Symbiosis by Harvest (%)				Dry Matter Yield (pounds/acre)
	1	2	3	Mean	
Hay and pasture legumes					
Alfalfa*	49	81	58	63	6,809
Red Clover*	51	79	65	65	6,230
Birdsfoot trefoil*	27	67	25	40	4,880
	Harvest at Grain Maturity				
Grain legumes					
Soybean†			76		2,494
Soybean‡			52		7,837

*Established in soil with 3.7% organic matter and an initial NO_3^--N concentration of 12 ppm (0- to 6-inch depth).
†Established in soil with 1.8% organic matter and an initial NO_3^--N concentration of 12 ppm (0- to 8-inch depth).
‡Established in soil with 4.8% organic matter and an initial NO_3^--N concentration of 31 ppm (0- to 8-inch depth).

Table 4. Seasonal dinitrogen fixation by forage and grain legumes (Heichel, 1987a).

Crop	Seasonal N_2 Fixation by Year of Stand (pounds/acre N)			
	1	2	3	4
Alfalfa	142	102	143	199
Red clover	118	61	77	68
Birdsfoot trefoil	100	44	87	97
Soybean 1*	13-75			
Soybean 2†	68-135			

*Grown on high-N soil (see table 3).
†Grown on low-N soil (see table 3).

Table 5. Seasonal total of dinitrogen fixation by hay and pasture legumes and legume-grass swards (Heichel, 1987a).

Species	N_2 Fixation (pounds/acre N/growing season)	Location
Alfalfa	189	Lexington, KY
Alfalfa	102-199	Rosemount, MN
Alfalfa-orchardgrass sward	13-121	Lucas Co., IA
Alsike clover	19	New Jersey
Birdsfoot trefoil	44-100	Rosemount, MN
Crimson clover	57	New Jersey
Hairy vetch	99	New Jersey
Ladino clover	147-168	Maryland
Red clover	61-101	Rosemount, MN
Subterranean clover	52-163	Hopland, CA
Subterranean clover-soft chess sward	19-92	Hopland, CA
Sweetclover	4	New Jersey
White clover	114	Lexington, KY

Table 6. Seasonal total of dinitrogen fixation by seed or pulse legumes. (Heichel, 1987a).

Species	N_2 Fixation (pounds/acre N/growing season)	Location
Chickpea	21-75	Alberta
Common bean	11-108	Alberta
	2-98	Alberta
Faba bean	159-224	Alberta
Field pea	155-175	Alberta
Lentil	149-169	Alberta
Soybean	12-67	Iowa
	20-71	Minnesota
	49-143	Arkansas
	243-277	Washington
	49-115	Minnesota
	93	Nebraska

Table 7. Nitrogen budget of soybeans illustrating the allocation of soil and symbiotic N among plant components and the net return of N to the soil with 40% and 90% of plant nitrogen from symbiosis (Heichel, 1987a).

Crop Component	Dry Matter Content	Total Reduced N Content	Content of Symbiotic N		Soil N Export in Grain		Symbiotic N Return in Residue		Loss (-) or Gain (+) or N	
			40% N Symbiosis	90% N Symbiosis	40% N	90% N	40% N	90% N	40% N	90% N
	pounds/acre N									
Grain	2,100	151	61	136	90	15	-	-	-	-
Residue*	3,424	40	16	37	-	-	16	37	-	-
Total Plant	5,524	191	77	173	-	-	-	-	-74	+22

*Pod walls, leaves, stems, roots and nodules; incomplete grain harvest would increase this value.

Table 8. Nitrogen budget for seeding-year alfalfa illustrating the net return of nitrogen to the soil with two moldboard plowing practices (Heichel, 1987a).

N From	Plant Part	N (pounds/acre) at Harvest on July 12	August 30	October 20
N_2 fixation	Total	51	91	30
	Herbage	46	66	20
	Root and crown	5	25	10
Soil	Total	54	22	23
	Herbage	48	16	14
	Root and crown	6	6	9
N budget with plowing on August 30				
	N return/harvest	-43*	+91	
	Cumulative N	-43	+48	
N budget with plowing on October 20				
	N return/harvest	-43	+ 9	+30
	Cumulative N	-43	-34	- 4

*N return/harvest = fixed N in roots and crowns returned by soil (5 pounds/acre) soil N removed in herbage (48 pounds/acre) = -43 pounds/acre.

Table 9. Fertilizer N replacement value of various forage legumes managed as green manures or as hay, plowed under in the fall, and planted to corn the subsequent year (Heichel and Barnes, 1984).

Legume	Fertilizer N replacement value (lb N/acre)	Location
Alfalfa (winterdormant)	8[a]	Iowa
	40-84	Minnesota
	120-150[a]	Minnesota
	150	Illinois
	100-160	Iowa
Alfalfa (non-winterdormant)	50[a]	Iowa
Birdsfoot trefoil	84	Minnesota
Ladino clover	12[a]	Iowa
Red clover	22[a]	Iowa
	84	Minnesota
	120-150[a]	Minnesota
Sweet clover	100[a]	Iowa
	120-150[a]	Minnesota

[a]Legume managed as green manure (no legume harvest). All others managed as hay with various cutting schedules.

Table 10. Corn grain yields as influenced by previous crop and N fertilizer rate at Waseca, MN (Hesterman et al., 1986).

N rate	Corn grain yield following 1 year of				
	Corn	Soybeans	Wheat	3-cut alfalfa	1-cut alfalfa
lb/acre	bu/acre				
0	50	58	57	80	115
50	65	90	99	124	137
100	100	122	128	137	139
150	103	138	127	138	138
200	100	140	144	145	145

Table 11. Fertilizer-N replacement values for corn following 1 year of alfalfa and soybeans at four Minnesota locations (Sheaffer et al., 1989).

First year crop	Harvest system	Fertilizer-N replacement values				
		Becker	Lamberton	Rosemount	Waseca	Location mean
		lb N/acre				
Alfalfa	3-cut	47	91	125	84	87
	1-cut	64	93	131	190	120
Soybean		2	75	48	26	38

Table 12. Recovery of nitrogen in residues of medic (tops and roots, topsoil-field (Ladd et al., 1981).

N Addition (pounds/acre)	Assay Crop		Legume N Recovery (% of addition)	
	Species	Growth period	Crop 1	Crop 2
43	Wheat (whole plant)	8 months	27.8	-
	Wheat (tops)	8 months		4.8
43	Wheat (whole plant)	8 months	20.2	-
21	Wheat	8 months	22.4	4.3
43	(tops)	8 months	24.9	4.1
86	(tops)	8 months	21.1	3.3

Table 13. Recovery of nitrogen-15 from alfalfa residue (% of input) by a subsequent corn crop at two Michigan locations. Values are averaged over alfalfa plant parts (shoots and roots/crowns) and times of incorporation (fall or spring) (Harris and Hesterman, 1987).

Plant Part	^{15}N Recovery (%) by Location	
	East Lansing	Kellogg
Grain	10.1 (0.9)*	15.9 (1.8)
Stover	6.1 (0.6)	8.3 (0.7)
Root	0.5 (0.0)	0.8 (0.1)
Whole plant	16.6 (1.4)	25.0 (2.2)

*Standard error shown in parenthesis.

IMPROVING LIVESTOCK AND POULTRY MANAGEMENT PRACTICES TO REDUCE NUTRIENT CONTAMINATION OF GROUNDWATER

by

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IMPROVING LIVESTOCK AND POULTRY MANAGEMENT PRACTICES TO REDUCE NUTRIENT CONTAMINATION OF GROUNDWATER

By John M. Sweeten, Ph.D., P.E.[1]

INTRODUCTION

Animal agriculture (livestock and poultry) accounted for $80.2 billion or 53 percent of the gross agricultural receipts (not including government payments) in the United States in 1988, exceeding the contribution of crops. Livestock and poultry production facilities can sometimes contribute to excess nutrients, salts, organic matter and other constituents in groundwater aquifers if manure and wastewater are not properly managed. Potential sources of groundwater contamination include open unpaved feedlots, runoff holding ponds, manure treatment and storage lagoons, manure stockpiles, and crop and pastureland used for land application of manure and wastewater. Dead animal disposal, and insecticide spray equipment, dipping vats and disposal sites for waste pesticide, rinsate or containers may contribute to localized groundwater contamination. Manure accumulations around livestock watering locations, intermittently-used stock pens, and livestock grazing operations that can vary from sparse range lands to intensively-stocked pastures may also influence the water quality of streams and aquifers.

This report identifies production practices that may contribute to groundwater contamination and provides a summary of research results and management strategies for groundwater pollution control for open feedlots, holding ponds and lagoons, and areas used for land application of manure and wastewater.

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The purposes of this report are to identify and assess: (1) the relationship of livestock production to nutrient contamination of groundwater; (2) technology and management practices to reduce potential for nutrient contamination of groundwater for livestock and poultry operations; and (3) public policy that could foster development and adoption of such practices.

LIVESTOCK AND POULTRY MANURE PRODUCTION IN THE UNITED STATES

Livestock and poultry manure resulting from concentrated and confined animal feeding facilities in the United States is a valuable resource for fertilizer, feedstuff or fuel. Manure is widely used as an organic fertilizer in many areas. Certain types of manure may also receive limited use in specialized situations as a feedstuff, as a substrate for anaerobic digestion to produce biogas (methane), or as fuel for combustion/gasification for electric power generation. However, these latter uses return all or a portion of the original manure fertilizer value as a residue that eventually is applied to land.

1974 Assessment of Manure Production and Distribution

Van Dyne and Gilbertson (1978) reported estimates of manure and nutrients produced by livestock and poultry in 3,050 counties in the United States based on animal numbers as reported in the 1974 Census of Agriculture. Estimates were developed on a dry weight basis both of (a) manure and nutrients voided (i.e. fresh manure), and (b) manure and nutrients remaining for use following proper accounting for losses occurring from volatilization, runoff, and infiltration. Van Dyne and Gilbertson (1978) took into consideration predominate types of manure and wastewater handling systems on a regional basis in developing estimates of nutrient losses, which are influenced by manure moisture content, collection method and frequency, type and duration of

nationwide. This ratio ranged from 0.09 dry tons per acre in the West/South Central (i.e. Southern Great Plains) to 0.51 dry tons per acre in the Northeast. Across all 3,050 counties, the range was from less than 0.01 dry tons per acre in numerous counties to a high of 1.8 dry tons per acre in one county in Georgia (poultry manure), considering all manure after losses per acre of cropland and pastureland.

The manure production values reported by Van Dyne and Gilbertson (1978) were based on standard values adopted by the American Society of Agricultural Engineers (ASAE, 1976). These standard values indicated weight of manure and constituent production per unit weight of live animal and have been widely used for engineering design of livestock waste management systems.

Current Estimate of Manure Production

However, these standard values were recently updated to reflect current research data (ASAE, 1988). In most cases, average values of dry manure and nutrients (pounds per day per 1,000 pounds liveweight) were revised upwards, and standard deviations were calculated to reflect the degree of variability. These data can be used to calculate daily manure production in terms of solids, oxygen demand, macronutrients, micronutrients and salts.

Recent estimates of livestock and poultry numbers in the U.S. based on USDA production statistics are shown in Table 2. Maps showing the distribution of livestock and poultry production within states are published by State Crop and Livestock Reporting Services.

Using the revised ASAE (1988) manure production values, together with the livestock and poultry statistics in Table 2 and assumed average animal liveweights, the total U.S. manure and nutrient production by livestock and poultry was estimated in Table 2. The total quantity of manure solids, N, P

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and K initially voided according to these estimates is approximately 158 , 6.5, 2.0, and 4.1 million tons per year on a dry weight basis.

According to these estimates, extensive production of livestock (on pastures and ranges) would contribute a large proportion of the manure voided. This manure recycles back through the soil and plant system but is largely uncollectible and is therefore "unmanageable." Beef cattle in extensive production systems contribute about seven-eighths of the total for beef cattle versus only one-eighth for beef cattle on feed. The same appears to be true of sheep. Of the dairy cattle manure, as much as half or two-thirds might be voided on pastures, depending on the types of production systems, season, climatic region, and herd size. However, as dairy operations increase in size the trend to total confinement is expected to continue. Essentially none of the poultry are produced under extensive systems.

For intensive animal production systems (i.e. predominantly in confinement), the predominant sources of voided manure (in terms of solids and nitrogen) appear to be dairy cattle, swine, beef feedlot cattle, broilers, turkeys, and laying hens. However, in terms of phosphorus and potassium production, swine are the leading species. These estimates do not include horses, which tend to be concentrated near urban areas.

Intensive Production Systems

The U.S. Environmental Protection Agency (USEPA) published a description of the types of intensive livestock confinement systems and a tabular summary of the manure quantities and characteristics resulting from each type of system (USEPA, 1973). The typical confinement density (i.e. animal spacing) of each type of intensive production system was also listed. This report was

written in support of the eventual USEPA effluent guidelines and new source performance standards promulgated in response to PL 92-500.

White and Forster (1978) also identified major types of livestock and poultry production facilities and associated manure management systems. Cost estimates of each type of system were provided as a function of size of operation (i.e. number of head). The Midwest Plan Service (1987) has presented detailed design information on types of beef cattle feeding facilities, and the Pork Industry Handbook (Foster and Mayrose, 1987) contains similar information for swine facilities.

The systems identified in these reports are relatively current although the relative "mix" in terms of percentage of adoption of various systems will continue to shift within each region reflecting climatic considerations, economics, new technology and improved equipment.

For purposes of water pollution control, intensive livestock production systems may be regarded as "animal feeding operations" which are defined in the USEPA regulations for feedlots (USEPA, 1976) as being areas where animals are "stabled or confined and fed or maintained for a total of 45 days or more in any 12 month period, and...crops, vegetation, forage growth or post-harvest residues are not sustained in the normal growing season over any portion of the lot or facility." This condition usually develops where manure production and animal traffic are great enough and frequent enough to prevent germination or growth of forages, for example.

The USEPA definition is not specific as to animal species, type of confinement facility or animal density. Rather it tends to integrate these factors along with climate and soils into a single visually-determined

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criterion--i.e. the absence of vegetation, which has important surface and groundwater quality implications as follows:

1. Manure production exceeds normal plant tolerance levels.
2. Crop uptake is not a pathway for nutrient removal, so that runoff, leaching and volatilization pathways must be proportionately larger.
3. Runoff volume is greater and time of concentration is shorter as compared to a vegetated surface.
4. The important vegetative-filter mechanism for retardation of erosion and transport of sediment, nutrients and oxygen-demanding organic matter is not present.

Moreover, these conditions may persist long after livestock are moved from the confinement area.

Manure solids and nitrogen production rates (as-voided basis) within intensive systems vs. extensive livestock production systems were presented by Sweeten and Reddell (1978) as a function of animal density and spacing per unit liveweight. The solid manure generation rates have the following orders of magnitude: open lots--100 to 1,000 dry tons per acre; and confinement buildings--1,000 to 10,000 dry tons per acre per year (Figure 1).

Nitrogen production rates (as voided) may range from 10,000 to 100,000 pounds per acre per year for open lots and even greater within confinement buildings (Figure 2). When feedlot cattle are confined at spacings of 100 to 500 feet^2 per head (200 feet^2 per head perhaps being most common), essentially all infiltration and runoff from the feedlot surface comes into direct contact with the manure and has potential for pollutant transport.

Extensive Livestock Production Systems

Extensive systems for livestock production are characterized primarily by grazing operations and they consist primarily of ranges, pastures, and crop lands. This includes either wooded or open areas. Extensive livestock systems usually include feeding and watering sites, working corrals and buildings or sheds which are intermittently used and are generally dispersed.

Grazing cattle produce fecal deposits covering about one square foot area at an average frequency of 12 times daily (Marsh and Campling, 1970). These deposits remain on soil and plant surfaces up to 1¼ year depending upon climate, insect and biological activity. However, urine is absorbed by soil resulting in a quick forage response to applied nitrogen.

Livestock concentrations (animal density) may vary in grazing situations by 2 or 3 orders of magnitude from 10 to 5,000 pounds liveweight per acre, depending upon factors such as climate, soils, topography, and management intensity. Accordingly, manure voided varies from less than 0.5 to 7 dry tons per acre per year and nitrogen deposition ranges from approximately 1 to 500 pounds per acre per year for sparse rangelands to intensively grazed improved pastures, respectively (Sweeten and Reddell, 1978). Hence, direct defecation of manure nitrogen onto improved, intensively grazed pastures may be a factor in sustaining forage production. On rangeland, nutrient return through manure is almost inconsequential, and quality of runoff or infiltration may not be adversely affected by deposited manure.

The nonpoint source pollution potential of pastured livestock depends in part upon the stocking density, length of grazing period, average manure loading rate, manure spreading uniformity by grazing livestock, and disappearance of manure with time.

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Effects of livestock nonpoint sources on surface water quality were reviewed by Sweeten and Melvin (1985). Best management practices for controlling livestock NPS pollution were summarized from USEPA (1984).

LIVESTOCK AND POULTRY WATER REQUIREMENTS

The quantity and quality of groundwater is a major concern to livestock and poultry producers who rely on wells for water supply. If contamination of groundwater occurs, the livestock production facility would generally be first to be affected. Chemical quality must be assured both for animals and people including workers and their families that live on-premises or nearby. Groundwater quality may also be a concern in these areas:

1. Nutrient and mineral content of drinking water in relation to dietary needs;
2. Physical clogging of sensitive nipple- or cup-type waterers, foggers, sprinklers, etc., with debris, algae, or scale deposits; and
3. Scale formation in steam boilers or water heaters.

Livestock Drinking Water Quality

Water quality limitations for livestock drinking water have been recommended both by the National Academy of Sciences (NAS, 1974) and the Council for Agricultural Science and Technology (CAST, 1974). Their recommendations are shown in Table 3, alongside a comparison with current public drinking water standards for comparable constituents (Herrick, 1976; Faires, 1989). In general, livestock are apparently more tolerant to constituents of great concern to humans such as nitrates. However, there is variation among species. For example, suggested limits for total dissolved solids (TDS) are: poultry--2,900 ppm, swine--4,300 ppm, horses--6,400 ppm,

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dairy cattle--7,150 ppm, beef cattle--10,000 ppm, and sheep--12,000 ppm. On the average, a successive increase of 1,800 ppm TDS tends to eliminate one additional animal species insofar as production recommendations are concerned. Moreover, there are several species-specific limitations. For example, sheep are least sensitive to salinity, yet are most sensitive to copper as compared to other species.

The chemical constituent levels for livestock and poultry recommended by CAST (1975) and NAS (1974) should perhaps be reexamined periodically in the light of recent research and detection capabilities for organic and inorganic chemicals and veterinary diagnostic research. If necessary, new limits should be established and made widely available to livestock producers, water quality officials and the general public. This re-examination might also consider the potential for any possible human food-chain implications of, for example, accidental spills of hazardous chemicals from ruptured rail cars or illegal disposal of toxic chemicals in the vicinity of water supply wells for large livestock and poultry feeding facilities.

Water Quantity Required for Livestock

Another consideration with livestock and poultry feeding facilities is having adequate groundwater supply. The essential requirement for water consumption per animal varies widely according to body weight and environmental factors such as temperature and humidity. Some typical ranges of daily water consumption recommended for system design purposes by the Midwest Plan Service are shown in Table 4 (Palmer et al., 1979). Peak demands for livestock water occur in the hottest portion of the day. Also, depending on the type and design of individual facilities, additional water is needed for sanitation, manure removal, animal cooling, dust suppression, product

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storage (milk cooling, for example), or feed processing (steam flaking, grain soaking, etc.). These types of water requirements can vary from essentially zero to more than 100 gallons per cow per day for dairy operations, for example.

Price (1989) estimated that feedlot cattle consume 7 to 12 gallons of water daily under moderate temperatures and 20 to 35 gallons per day in extremely hot temperature (above 100°F). Cattle water consumption can also be estimated at 4 pounds water (or 0.48 gallons) per pound of dry feed consumed, and daily dry feed consumption is about 2% of body weight (Sweeten et al., 1986). Peak rate of consumption may be twice the average rate. Thus, an 800 pound animal will consume 16 pounds of dry feed and needs at least 7.7 gallons of water per day. By comparison, data from a west Texas beef cattle feedlot with 28,000 head capacity on a metered city water supply indicated an average consumption of 7.0 gallons per head per day, and a range of 4.2 to 10.3 gallons per head per day over a one-year period (Sweeten et al., 1986). Peak water requirements occurred from June to September and lowest levels occurred in the winter months.

For example, a 25,000 head cattle feedlot would need an average continuous pumping rate of 175 gallons per minute just to satisfy a 10 gallons per head per day basic water need of the livestock. If continuous overflow watering systems are used, the water use and pumping requirement might be doubled, i.e. 350 gpm per 25,000 head feedlot (Sweeten et al., 1986). Assuming the feedlot operates at an animal density of 250 feet^2 per head and covers 143 acres, this water usage requirement represents a continuous pumping rate of about 2.4 gpm/acre, or 47 acre-inches per acre per year. This is

about two or three times the average water use per acre on irrigated cropland in the surrounding areas (TWDB, 1986).

The pumping rate needed to supply these drinking water needs for large scale operations might be sufficient to create a continual cone of depression around the well. This cone of depression would induce groundwater flow toward the well and tend to recapture downward leached pollutants before their dispersal throughout the aquifer.

POTENTIAL GROUNDWATER POLLUTION PROBLEMS: LIVESTOCK AND POULTRY

CAUSES OF GROUNDWATER CONTAMINATION

Primary Constituents

Constituents in livestock and poultry manure that can cause groundwater contamination include those parameters that exceed concentrations in aquifers. Primarily these are pathogenic organisms, nitrates, and ammonia. Other constituents such as potassium, sodium, chloride and sulfate may also be leached and impair chemical quality of an aquifer. While phosphorus and organic solids are important concerns for surface water pollution, they are not generally implicated as groundwater pollution sources due to their limited leaching potential.

Potential Routes of Groundwater Contamination

Groundwater pollution from livestock and poultry manure can occur from several routes such as:

1. Well-head contamination--direct entry of runoff or leachate through active or abandoned wells. Contaminants of greatest concern would include nuisance bacteria, pathogenic organisms, nitrogen compounds, and organic-matter that impairs flavor.

2. Intermittently occupied livestock facilities--Infiltration/leaching of soluble nitrogen compounds (NH_3, NO_3 and NO_2) and salt ions would be of greatest concern for barnyards, corrals, feeding and watering sites, working-pens, travel lanes, etc.
3. Continuous confinement facilities--Infiltration or leaching of soluble nitrogen and salt compounds are of greatest concern for feedlots, working corrals, and confinement buildings.
4. Manure stockpiles and storage bunkers--infiltration of leachate and runoff.
5. Liquid manure storage ponds or treatment lagoons--seepage.
6. Runoff collection channels, debris basins and ponds--seepage.
7. Land application of manure (solid, semi-solid, and liquid form)--leaching.
8. Land application of wastewater and treatment effluent--infiltration and leaching.
9. Infiltration of manure-contaminated runoff or wastewater over aquifer recharge zone.
10. Dead animal disposal pits--leachate and seepage.
11. Livestock insecticide application sites (spray pens and vats).
12. Silos--leachate infiltration and runoff.
13. Disposal sites for insecticide containers and waste insecticide solutions (rinsate, dipping vat waste, etc.)--seepage and leachate.
14. Grain storage pits and stockpiles--infiltration of leachate and runoff.

Aquifer vulnerability to infiltration and leaching of pathogens, nutrients, salts and organic matter from these sources is subject to the same

mechanisms as other types of groundwater pollutant sources. Aquifer vulnerability can be characterized by the DRASTIC model (Aller et al., 1987), which provides a numerical index according to the following 7 parameters:

D - Depth to water
R - Annual recharge
A - Aquifer media
S - Soil media
T - Topography
I - Vadose zone impact
C - Hydraulic conductivity

These factors have been organized to create the acronym DRASTIC.

PRODUCTION TRENDS THAT IMPACT GROUNDWATER QUALITY

There are obviously general trends toward use of confinement buildings, toward larger feeding facilities and away from labor-intensive manure handling systems. In confinement buildings there is increased use of either manure flush systems or mechanical scrapers, which provide for manure collection as often as several times per day.

Flush/Lagoon/Irrigation Systems

Use of flush systems requires approximately 8 to 12 gallons of water to remove and transport one pound of dry solids along a concrete floor or channel entirely by gravity. This is at least twice the water requirement for manual scraping and floor washing. Because of the large volumes of water use, large earthen lagoons for storage and partial biological treatment of manure and wastewater are usually necessary. Lagoons are desirable to maximize nutrient loss where land is insufficient. These systems may cover several acres, and necessitate that groundwater pollution potential be minimized by proper location, design and management. Lagoon effluent usually has considerable nitrogen concentration such that land application rates are nitrogen limited, but solids concentrations are low (usually 1.0% or less) and volumes are

sufficient to favor application by irrigation rather than hauling. Low, frequent, uniform applications are needed to avoid runoff and excessive nutrient leaching.

Mechanical Scrapers/Storage Pit/Tank Wagon Transport

Another way to achieve daily collection of manure in confinement buildings to reduce nuisance potential and promote animal sanitation is mechanical (cable or motorized) scrapers. In contrast to flushing systems minimal amounts of supplemental water are needed. Consequently, a much smaller storage structure is needed, usually supplied by concrete tanks or small earthen pits. The relatively high solids concentration make it convenient to use tank wagons or tank trucks for direct transport to fields where surface spreading or soil injection may be practices. Due to the relatively high nutrient concentrations, much lower volumetric application rates per acre must be observed as compared with lagoon effluent. The smaller size, use of concrete construction and necessity of management attention in land application should generally lessen the groundwater pollution potential as compared to lagoon systems.

Open Feedlots with Solids Collection/Runoff Control

Climates with more than 30 inch moisture deficit (evaporation minus runoff) and moderate winters are favorable for open unpaved feedlots for cattle (beef and dairy) and sheep. Open feedlots are generally more economical than confinement buildings.

Manure in solid form is scraped at intervals ranging from weekly to annually and stacked in pens or in outside stockpiles prior to land application. Rainfall runoff is collected in runoff holding ponds and irrigated on croplands of pasture lands. The volume of rainfall runoff

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collected generally ranges form 25 to 60% of annual rainfall. In dry climates, evaporation is often used for disposal of feedlot runoff. Groundwater pollution potential exists from leaching through feedlot surfaces, stockpiled manure and land-applied manure and effluent and from seepage from runoff holding ponds. Open lot feeding systems range in size from less than 100 head to more than 100,000 head. Some of the general trends include toward consolidation of ownership, fewer but larger facilities, more frequent solid manure collection, off-site marketing of solid manure, use of composting to reduce manure volume and improve demand for crop fertilizer or horticultural uses, use of lower application rates, and expansion of land ownership by feeding operations. However, utilization of feedlot runoff holding pond effluent is not increasing, and the use of overflow watering systems that encroach on design storage capacities of runoff holding ponds appears to be on the increase.

MANAGEMENT PRACTICES AND EFFECTS ON GROUNDWATER CONTAMINATION

This section of the report provides a summary of research results on groundwater pollution control for open feedlots, for holding ponds and lagoons, and for land application of manure and wastewater. It provides management strategies that will decrease the potential for groundwater pollution.

Feedlot Surfaces

Research in several states, under climatic conditions ranging from arid to humid, has determined that an active feedlot surface develops a compacted manure/soil interfacial layer (usually 2 to 4 inches thick) which provides an excellent moisture seal. This compacted manure/soil layer reduces the water infiltration rate to less than 0.002 inches per hour, or as little as 3

percent of the infiltration rate of the underlying soil (Mielke et al., 1974; Mielke and Mazurak, 1976). This zone of low infiltration restricts leaching of salts, nitrates and ammonium into the subsoil and underlying groundwater (Schuman and McCalla, 1975). This interfacial layer is usually dark brown or black, often resembling charcoal perhaps due to iron sulfide content (Norstadt et al., 1975). It is composed of bacterial cells, organic matter, degradation products, and soil particles.

Self-Sealing of Soil Surface

McCalla and Elliot (1971) found that reducing conditions are present at soil depths of 1-5 feet beneath a cattle feedlot. These reducing conditions are evidenced by the presence of methane and reduced oxygen levels in soil air beneath feedlots as compared to a cropped field. High carbon dioxide levels indicate presence of organic matter. The presence of both reducing conditions and organic matter indicates favorable conditions for dentrification, and hence provides protection against nitrate leaching.

If an undisturbed anaerobic layer of compacted manure is left above the manure/soil interfacial layer, formation and leaching of nitrate is retarded in favor of dentrification (Stewart et al., 1967; Chang el al., 1973). With this type of anaerobic condition, nitrate is converted to nitrogen gas which is released to the atmosphere rather than being leached to subsoil and groundwater. The best soil profile to retard nitrate and nitrite movement and retain salts near the soil surface was found to be sandy topsoil above a clay loam subsoil (Norstadt and Duke, 1982).

To avoid disrupting the surface seal provided by the manure/soil interfacial layer, feedlot personnel should be taught correct use of manure collection machines (wheel loaders or elevating scrapers) to "harvest manure"

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rather than "cleaning pens." Leaving an undisturbed "manure pack" will also result in collecting the highest quality manure for crop fertilization or energy generation (Sweeten et al., 1985). Feedlots that have been abandoned without manure removal may offer greater potential for groundwater pollution than active feedlots (Madison and Brunett, 1984).

Nutrient Leaching

Concentrations of nitrate and ammonia decrease rapidly within the top foot (30 cm) of the feedlot soil layer (Figure 3) (Schuman and McCalla, 1975). Soil water samples taken at about 3 feet beneath cattle feedlots showed concentrations of NO_3, P, Mg, and total solids that are similar to that under adjacent cropland (Alego et al., 1972; Elliott et al., 1972; Schuman and McCalla, 1975; Dantzman et al., 1983).

Miller (1971) measured groundwater quality in the Ogallala Aquifer beneath 80 cattle feedlots in the Texas High Plains and determined that about one-fourth had contributed to nitrate levels that approached or exceeded the USEPA drinking water standard of 10 ppm NO_3-N in the immediate vicinity of the feedlots. Seepage rates were estimated at 2 to 20 x 10^{-6} cm per second (0.003 to 0.03 inches per hour) under feedlot surfaces and playas used for runoff collection.

Borman (1981) monitored water quality in an alluvial aquifer using 19 observation wells around a 90,000 head feedlot from startup through 4 years of operation. Chloride concentrations increased slightly in one well downgradient from a runoff-retention pond. Leachate had percolated to 5 feet depth beneath the feedlot but not to 20 feet. The small observed changes in groundwater quality were attributable to an impermeable manure pack, soil clogging under the cattle pens, limited available recharge, dentrification in

the unsaturated zone, and soil clogging under the unlined runoff retention pond.

Kreitler (1975) has developed a technique for differentiating between nitrate in soil and groundwater caused by animal wastes versus natural soil material or commercial fertilizer. It is based on the use of an N-15 isotope technique.

Holding Ponds and Lagoons

Self-Sealing

Seepage from livestock waste treatment lagoons and runoff holding ponds has also been studied by researchers for at least two decades. In essence, it has been determined that bacterial cells and fine organic matter generally clog soil pore spaces along the bottom and sides of lagoons and holding ponds (Barrington and Jutras, 1985) making them effectively "self-sealing" (Davis et al., 1973).

After several months of storage, coefficients of permeability of the soil at the bottom of ponds storing liquid manure, wastewater and runoff from livestock operations have usually been from one to three orders of magnitude (i.e. 10 to 1000 times) lower with wastewater than for clean water, as indicated in Figure 4 (Robinson, 1973; Lehman and Clark, 1975; Barrington and Jutras, 1983). Where the bottom and sides of manure storage ponds and lagoons has a moderate to fine-textured soil (such as silt, clay loam, or clay), the final permeability coefficient is usually of the order of magnitude of 10^{-6} to 10^{-7} centimeters per second (cm/sec), or 0.00014 to 0.0014 inches per hour, respectively (Barrington and Jutras, 1985). However, final permeabilities of a sand usually exceed 10^{-6} cm/sec (0.0014 inches per hour) (Dye et al., 1984).

Cattle manure has generally shown better self-sealing properties than swine manure (Barrington and Jutras, 1985).

Livestock manure and wastewater do provide significant beneficial self-sealing on the bottom and sides of lagoons and holding pens. However, some regulating agencies feel this phenomenon should not be counted on as the sole means of groundwater protection and that lagoons should also be placed in relatively impermeable subsoils (Dye et al., 1984).

Many feedlots in the Southern Great Plains are built on playa lakes, which have a natural clay bottom of several feet thickness that is underlain by much more permeable soil material (of Pleistocene origin) which resembles caliche. Lehman and Clark (1975) determined that undisturbed cores of the clay surface soil in playas had permeability values with clear water of 2.8 x 10^{-5}0.10 cm/sec (0.04 in/hr) as compared to 1.1 x 10^{-3} cm per sec (1.6 in/hr) for the buried Pleistocene materials. However, the addition of feedyard runoff reduced permeabilities to only 8.3 x 10^{-4} inches per hour (5.6 x 10^{-7} cm/sec) through the natural clay bottom after 10 days and to 0.0025 inches per hour (1.7 x 10^{-6} cm/sec) for the underlying buried soil within 45 days.

Nutrient and Salt Leaching

The leaching of contaminants in feedyard runoff below a playa lake bottom was investigated by Lehman et al. (1970). Nitrogen compounds did not move below 3 feet. At 2 feet and below, the nitrate and nitrite concentrations were only slightly higher than for playas that did not receive feedyard runoff (Table 5).

The feedlot playa study was repeated 5 years later by Clark (1975). Results in Figures 5 and 6 show that both nitrate and chloride concentrations decreased drastically within the top meter. Below 1 meter (3.3 feet) depth,

nitrate concentrations were less than public drinking water standards of 10 mg/l nitrate-nitrogen.

The potential for groundwater contamination is increased (Lehman and Clark, 1975) when playa lake bottoms are excavated below the natural clay layer. An alternative is to stockpile the clay and reapply to a compacted depth of one foot or more over the bottom and sides to serve as a clay liner (TWC, 1987).

Monitoring wells placed in the vicinity of livestock waste treatment lagoons and holding ponds have been used to evaluate the distribution of groundwater contaminants caused by lagoon seepage (Collins et al., 1975; Ciravolo et al., 1979; Sewell, 1978; Ritter et al., 1981; Phillips and Culley, 1985). Nutrient or salt concentrations sometimes increase in shallow groundwater in the immediate vicinity of lagoons or holding ponds. However, these initial increases usually diminish after several months. These results are reasonably consistent with the observed reductions in permeability caused by self-sealing.

Regulatory Requirements for Soil Material

The USEPA regulations for confined livestock and poultry operations deals only with surface water protection and does not include requirements for groundwater protection. Several states and local entities do have groundwater protection requirements. For example, The Texas Water Commission (TWC, 1987) regulation that governs confined, concentrated livestock and poultry feeding operations requires groundwater protection for lagoons and holding ponds. The regulation requires that all wastewater retention facilities be constructed of compacted or in-situ soil materials of 12 inches minimum thickness with low permeability. The soil material must meet or exceed the following criteria:

liquid limit of 30 percent or more, plasticity index of 15 or more, and fraction passing a number 200 mesh sieve of 30 percent or more. These standards in essence define a clay or clay loam soil with appreciable shrink-swell characteristics.

If these soil standards for lagoons and holding ponds are followed, along with the benefit of self-sealing from stored manure and wastewater, groundwater pollution should not be a problem. Moreover, cumbersome requirements such as monitoring wells or impermeable membrane liners may not be necessary.

Land Application of Wastes

It is essential that livestock manure and wastewater be collected, stored and applied to land to prevent discharge to surface water. The hourly application rate for irrigated wastewater should be uniformly less than the soil infiltration rate to prevent surface runoff. Manure and wastewater should be applied to soils at annual rates that match crop yield goals and expected plant uptake of nutrients to assure that nutrients are used efficiently and that groundwater contamination is not likely.

Yields from Manure Application

With proper manure fertilization rates such as 10 tons of feedlot manure per acre, crop yields that equal or exceed the yields from commercial fertilizer have usually been observed as shown in Table 6 (Mathers and Stewart, 1984). Yields with manure are often sustained for several years longer after manure application than with commercial fertilizer due to the slower release of residual nutrients and micronutrients (Lund et al., 1975; Lund and Doss, 1980).

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A method for determining proper manure application rates based on nitrogen content was developed by the USDA Agricultural Research Service (Gilbertson et al., 1979). This technical guide takes into account the slow rate of release of organic nitrogen in manure. Recommended manure application rates per 100 pounds of available nitrogen are shown in Table 7. For example, suppose cattle manure contains 2% nitrogen on a dry matter basis. As shown in Table 7, it takes 7 tons of manure dry basis the first year to supply 100 pounds per acre of available nitrogen. In succeeding years, release of residual organic nitrogen lowers the manure requirement to 5.8 tons per acre in the second year and to 4.4 tons per acre in the fifth year. Because of nitrogen losses after manure is applied to soil, application rates listed in Table 7 should be increased by approximately one-third if manure is to be surface-applied rather than incorporated into the soil.

Nutrient Accounting

With proper manure application rates, most of the applied nutrients can be accounted for in increased harvested tonnages of crop (grain, forage, crop residue, etc.) or gain of pastured cattle. On the other hand, excessive manure application rates usually do not increase yields appreciable and they increase the soil nitrate level to levels that exceed 10 ppm NO_3-N (Figures 7 and 8) (Reddell, 1974; Mathers and Stewart, 1984; Westerman et al., 1983).

Some research projects have documented crop nutrient uptake as a percent of applied nutrients. For example, Westerman et al. (1978) determined that uptake of N-P-K by coastal bermudagrass was 74, 41 and 74%, respectively, for swine lagoon effluent application rates that matched the recommended soil N needs. But plant uptake of N-P-K was only 33, 17 and 32% when N application

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was 4 times the soil/plant requirements. Part of the remaining 67% applied N was subject to leaching (Figure 7).

Nitrogen and phosphorus accumulate in the root zone following manure applications that greatly exceed crop nutrient requirements (Figure 9) (Murphy et al., 1972; Manges et al., 1975; Reddell et al., 1974) and may be subject to leaching. The fraction of nutrients in the soil that actually leach, volatilize, dentrify, or are taken up by crops for typical livestock and crop production systems needs further research in many areas.

Soil Testing

A great deal of the agricultural soil has low nitrogen, organic matter and micronutrient status and can benefit greatly from manure application. Technical guides to proper manure application and accurate soils analyses can be obtained from the Extension Soil/Water Testing Laboratories in most states or from commercial laboratories. Fertilizer recommendations for specific crops are available from Cooperative Extension Services through County Extension Agents and Extension Agronomists. These fertilizer guides specify the pounds of N, P_2O_5 and K_2O needed to produce specific crop yields. For the crop yield to be met, the crop must have ample fertilizer and water. For effluent that is nutrient-limited, supplemental irrigation water may be needed to meet the yield goal and hence expected nutrient uptake.

Producers should annually sample and test soils for nutrient status and the nutrient and salt concentrations in manure and wastewater to guide future fertilization practices for achieving plant yield goals. This is both a good agricultural practice and an excellent groundwater protection measure.

Summary

Feedlot surfaces should be managed to maintain an undisturbed layer of compacted manure and a manure/soil interfacial layer over the underlying soil surface to restrict leaching of nutrients and salts. When feedlots are closed, however, all manure should be removed. Significant self-sealing of soil at the bottom and sides of storage lagoons and holding ponds for manure and wastewater does occur due to soil clogging with organic matter and bacterial cells but this does not form a complete seal. Fine-textured compacted soils are needed in most instances to control seepage. Applying manure and wastewater according to crop nitrogen requirements will prevent groundwater contamination in most cases. However, excessive application rates can contribute to contamination of underlying aquifers with nitrate ammonia, potassium, and chloride.

RECOMMENDATIONS FOR FURTHER STUDY AND TECHNOLOGY DEVELOPMENT

Technologies Needing Expanded Adoption or Development

1. Manure utilization technologies--marketing, composting, biogas, thermochemical conversion, fiber recovery, etc.
2. Land application--economic guidance to farmers, soil testing to help define limits of application rates, improved cropping systems (Maximize nutrient uptake).
3. Nutrient losses--magnitude of losses in lagoons, storage tanks, and land application needed to be better defined as a function of design, operating and climatic variables to allow accurate modeling of nutrient balances and development of nutrient management plans.
4. Isotope tracing of nitrate from animal wastes vs. commercial fertilizer and soil NO_3 to separate groundwater pollution caused by livestock sources from that contributed from natural sources and from commercial fertilizer.
5. Biotechnology--to reduce manure production and nutrients.
6. Demonstration Farms--in high and low groundwater pollution potential areas.
7. Develop BMP's for different segments of livestock and poultry industry with focus on groundwater protection.
8. Improve economic incentives for farmers to use manure in high manure production areas.
9. Definition of vulnerable aquifers using DRASTIC model vs. livestock distribution.

Policy Recommendations

1. Develop and demonstrate joint venture between state, cities, industry and agriculture to promote manure processing and/or utilization on public and private lands.
2. EPA effluent guidelines for feedlots should be modified to include requirements for groundwater protection and appropriate measures.
3. Increase Federal and State R&D in livestock waste management and particular focus on groundwater pollution abatement.
4. Cost sharing programs (through ASCS-USDA) should be provided for livestock and poultry feeders, ranchers and grazers to implement water quality protection practices in areas with water quality problems and groundwater pollution potential.
5. Increase the resources available for technical assistance (through SCS-USDA), education (through Cooperative Extension Service) and research (State Agricultural Experiment Stations and ARS-USDA). This will promote interface with state regulatory officials for mutual benefit of programs and will provide a higher level of service to producers and allow timely response, where necessary.

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Table 1

TOTAL MANURE AND NUTRIENT PRODUCTION
IN THE U.S. FOR 1974 (VAN DYNE AND GILBERTSON, 1978)

	Manure Dry Weight	Nitrogen N	Phosphorus P	Potassium K
	----------1,000 tons per year----------			
1. Initially Voided	111,562	4,083	1,039	2,390
2. Remaining After Losses	99,604	2,618	983	2,305
3. Economically Recoverable	52,169	1,384	506	1,231

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Table 2

ESTIMATED US LIVESTOCK AND POULTRY MANURE VOIDED,
USING 1988 ASAE MANURE PRODUCTION AND CHARACTERISTICS

Species	No. Animals 1000 head	Average Liveweight lbs.	Total Liveweight Billion lbs	Manure dry weight	Nutrients N	P	K
				million tons/year			
Cattle Inventory (January 1, 1989)							
a. Beef cows and heifers	33,669	850	28.619	44.917	1.776	0.475	1.097
b. Cattle on feed	9,408	800	7.526	11.813	0.467	0.125	0.288
c. Calves, stock cattle, etc. on range and pastures (by subtraction)	46,190	550	25.405	39.872	1.576	0.422	0.974
d. Dairy cows and heifers	10,217	1300	13,282	29.088	1.091	0.228	0.703
Subtotal--all cattle and calves	99,484	752	74.832	125.690	4.910	1.250	3.062
Hogs and Pigs Inventory (Dec, 1988)	55,299	140	7.742	15.542	0.734	0.456	0.734
Sheep Inventory (Jan 1, 1989)							
a. Sheep and lambs of range/pastures	9,189	85	0.781	1.568	0.058	0.012	0.046
b. Sheep and lambs on feed	1,613	60	0.097	0.194	0.007	0.001	0.006
c. Sheep and lamb inventory	10,802	81	0.878	1.762	0.065	0.013	0.052
Poultry Inventory							
a. Laying hens (Dec, 1986)	280,500	4	1.122	3.276	0.174	0.061	0.063
b. Turkeys (1988 annual production, ÷ 1.75 turnovers)	138,300	15	2.075	4.543	0.235	0.087	0.091
c. Broilers (1988 annual production, ÷ 5.5 turnovers)	951,900	2	1.904	7.644	0.382	0.104	0.139
al			88.553	158.457	6.500	1.971	4.141

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Table 3

RECOMMENDED LIMITS OF CONCENTRATION OF SOME POTENTIALLY TOXIC SUBSTANCES IN DRINKING WATER FOR LIVESTOCK (HERRICK, 1976)

Substance	Safe Upper Limit of Concentration (mg/l)			
	Humans U.S. EPA		Livestock	
	Primary	Secondary	NAS, 1974	CAST, 1974
Arsenic	0.05		0.2	0.5
Barium	1.0			
Boron				5.0
Cadmium	0.01		0.05	0.5
Chromium	0.05		1.0	5.0
Cobalt			1.0	1.0
Copper		1.0	0.5	0.5
Fluoride			2.0	3.0
Iron		0.3	--	--
Lead	0.05		0.1	0.1
Manganese		0.05	--	--
Mercury	0.002		0.01	0.01
Nickel			1.0	
Nitrate-N	10.0		100.0	300.0
Nitrite-N			10.0	10.0
Vanadium			0.1	1.0
Zinc		5	25.0	25.0
Selenium	0.01		--	--
Silver	0.05		--	--
Sulfate	250		--	--
Salinity TDS	500		<3,000[a]	--
	--		3,000-	--
	--		7,000[b]	--
			>7,000[c]	

[a] no serious risk
[b] reasonably safe
[c] Considerable risk

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Table 4

DRINKING WATER USE PER ANIMAL (Palmer et al., 1979)

Animal Species	Daily Water Consumption, gallons per head
1. Cattle	
a. Milking Cow	20-25
b. Dry Cow	10-15
c. Calves (1-1.5 gal/100 lbs)	6-10
d. Beef Cattle	8-12
2. Sheep	2
3. Horses	12
4. Swine	
a. Finishing Pig	3-5
b. Nursery Pig	1
c. Sow and Litter	8
d. Gestating Sow	6
5. Poultry	
a. Laying Hens	0.09
b. Turkeys	0.15

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Table 5

NITRATE, NITRITE AND AMMONIUM-NITROGEN CONCENTRATIONS
BENEATH PLAYA USED FOR FEEDLOT RUNOFF COLLECTION
(Lehman, Stewart & Mathers, 1970)

Depth	Feedlot Playa* (3 obs. wells)			Non-Feedlot Playa (2 wells)	
Feet	Nitrate	Ammonium	Nitrite	Nitrate	Nitrite
0	12.8	58.7	2.8	--	--
1	225	18.4	3.2	7.8	0.34
2	6.2	5.7	0.13	2.8	0.16
3	3.7	5.1	0.05	2.8	0.16
4	3.0	3.3	0.03	2.5	0.13
5	3.4	3.5	0.02		
6-13	0.3-2.7	1.1-2.8	0.02-0.12		

* Average of 3 center observation wells.

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Table 6

CROP YIELDS FROM FEEDLOT MANURE APPLICATION
BUSHLAND, TEXAS 1969-80, USDA-ARS
(Mathers and Stewart, 1984)

Manure Treatment	No. Years Applied	No. Years Recovery	Average Yields, lbs/acre/year Sorghum Grain 1969-73	Corn 1975 77, 79	Wheat 1976 78, 80
0	11	0	4,490	8,350	1,400
0 (N)	11	0	6,440	13,390	4,050
0 (NPK)	11	0	6,410	13,560	4,290
10	11	0	6,640	13,920	3,430
30	11	0	6,490	13,400	4,530
60	5	6	6,360	14,340	4,000
120	5	6	5,120	13,950	4,260
240	3	8	900	15,260	4,330
240	1	10	330	12,100	2,810

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Table 7

DRY TONS OF MANURE NEEDED TO SUPPLY 100 POUNDS OF AVAILABLE NITROGEN OVER THE CROPPING YEAR (GILBERTSON ET AL., 1979)

Years Manure is Applied	Nitrogen Content of Manure: % dry basis					
	1.0	1.5	2.0	2.5	3.04.0	
	----------Tons of dry manure/100 lb N----------					
1	22.2	11.6	7.0	4.6	3.1	1.4
2	15.6	9.0	5.8	3.9	2.8	1.4
3	12.7	7.7	5.1	3.6	2.6	1.4
4	11.0	6.9	4.7	3.4	2.5	1.3
5	9.8	6.3	4.4	3.2	2.4	1.3
10	6.9	4.9	3.7	2.8	2.2	1.3
15	5.6	4.2	3.3	2.6	2.0	1.2

A WASTE OF PRODUCTIVITY: AVENUES FOR IMPROVED MANAGEMENT AND APPLICATION OF WASTE TO AGRICULTURAL LANDS

by

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ABSTRACT

Sludge is an accumulation of the solids generated from wastewater treatment. Descriptions of primary, secondary, and tertiary treatment processes and the resulting sludge characteristics are included. Septage is a sludge produced from the individual home on-site treatment system using a septic tank and drainfield. Most sewage sludge now goes to municipal landfills (41%) and incinerators (21%) with no recovery of the nutrient components. Land spreading of sludge on agricultural lands now accounts for only 15% of the total but this method is growing rapidly. Maryland no land applies more than 90% of their sludge. Concerns over negative aspects of land application (i.e., odors, disease vectors, surficial and groundwater contamination) have caused some communities to delay or cease land appliation operations.

Composting is a popular pretreatment process that uses sewage sludge and produces and acceptable product. There are several examples of large composting operations producing and marketing the product to lawn and garden and agricultural markets.

While research is still expanding the knowledge and understanding of the fate of elements and pathogens in land spreading of sludge, a sound design procedure has been developed to determine loading rates. The nitrogen concentration in sludge is used to determine agronomic loading rates. Calculation of the annual and total loading rate (site life) of a heavy metal to a site can be determined knowing the application rate and characteristics fo the sludge. Research continues to evaluate the fate, availability, and pathway of the constituents of sludge as they move through the soil/plant system. Pathogen reduction processes are required in sludge treatment before land application to protect public health. Lag times between spreading and harvest and access limitations are required for certain crops to protect the food chain. Additional support to evaluation and monitor receiver systems and provide expanded educational programs will encourage public trust.

INTRODUCTION

Growing levels of sludge production in the United States (4 million tons in 1970 to 7 million tons in 1987) coupled with declining availability of disposal sites clearly indicate that alternative disposal methods are needed (Hart et al., 1988). Increasing application of wastewater treatment products on agricultural land has been suggested as a major alternative to other disposal methods.

Sludge application to agricultural and forestland has received increased research attention and studies indicate the potential for nutrient recycling in these systems. While land application allows for recycling of nutrients contained in sludge, it also provides the opportunity for introducing undesirable components into an agricultural system. Further, the nutrient content of waste by-products can be quite variable depending on the raw materials, treatment process, etc. (Sommers and Giordano, 1984).

A number of constraints to agricultural application of wastes exist dictated by the composition of the waste material to be used. Waste materials may contain a variety of undesirable components, including: (1) pathogens, (2) soluble salts, (3) heavy metals (e.g., Pb, Zn, Cu, Ni, or Cd), (4) trace elements (e.g., Se, Mo, or B), and (5) persistent organics (PCBs or chlorinated hydrocarbon pesticides) (Sommers and Giordano, 1984).

Chemical composition of the sludge along with the application rate will determine which one of these constraints applies to a given waste material. For example, pathogens are a greater problem in municipal wastes than industrial or agricultural wastes. Salts tend to be more of a problem in liquid wastes, particularly in irrigated regions. Heavy metals or trace elements exist in all sewage sludges, many industrial wastes, and few agricultural wastes. Thus, use of these wastes

as a nutrient source for crops will require "effective waste treatment processes (e.g., pathogen reduction), appropriate application rates (e.g., metals limitation), and best management practices (e.g., soil pH control)" (Sommers and Giordano, 1984).

Studies of the potential of certain forest ecosystems in Michigan to assimilate nutrients from liquid sludge applications have been very promising. Overall positive aspects of silvicultural sludge application include:

- o low risk of food chain contamination since forest crops are generally non-edible,
- o positive vegetative growth response to applications resulting in improved wildlife habitat and nutritional quality of forage plants,
- o a method of sequestering and removing elements from the site,
- o high permeability of forest soils allow for maximum moisture retention and thus reduced likelihood of surface runoff, and
- o sites typically are remote to population centers, reducing potential for human contact with sludge applications (Hart, et al., 1988).

However, the variability of nutrient cycling among different forest ecosystems requires that "site specific" application rates be determined in order to generate forest growth benefits in an environmentally sound manner. The Michigan studies indicate sludge application to forestlands to be economically and technologically feasible (Hart, et al., 1988).

Composting sludge with an organic material yields a nearly odorless humus-like material that is free of enteric pathogens. This product can be used as a soil amendment and is a minor source of plant nutrients (Table 1) (USDA, 1979). Indeed, composted materials applied at fertilizer rates may generate higher yields due to the associated improvements in soil physical properties. Composted materials have a variety of applications including: agronomic crops, in land reclamation efforts, nursery operations, turfgrass production.

Wastewater irrigation offers another recycling mechanism. Field experiments examining corn yield showed that 110 to 145 kg N/ha (67% of applied N) was assimilated by the crop under the wastewater irrigation regime as compared to 175 kg N/ha (58% of applied N) assimilation under NH4NO3 application (Sommers and Giordano, 1984). However, another study on nitrogen assimilation by grasses showed no appreciable difference between wastewater or conventional fertilizer application regimes (Sommers and Giordano, 1984).

Clearly, opportunities exist for increased use of wastewater treatment products in an agricultural setting. However, concerns over the addition of undesirable sludge components (i.e., heavy metals, trace elements, etc.) to agricultural systems require consideration. In addition, further information is needed on the fate of organic/inorganic N of wastes after field application in order to improve management practices and determination of appropriate application rates of wastewater treatment products.

TREATMENT METHODS AND PRODUCT CHARACTERISTICS

Sludge is the accumulation of solids generated in the process of treating wastewater. Typically wastewater is produced and delivered to treatment plants at the rate of about 150 gallons per person per day (Fair, et al., 1971). It contains material from the toilet, foodstuffs from the kitchen sink, soap, soil and greases from the laundry, and a wide variety of chemicals such as pesticides, fertilizers, paints, gasoline and oils. Homes, restaurants, grocery stores, gas stations, schools, and hospitals all generate wastewater and these sources are included in the average per capita per day value, listed above.

Most rural homes have their own sewage treatment system, usually a septic tank and drainfield trenches. The wastewater flows from the house into the septic tank where the solids settle to the bottom and floating matter is collected in the top. The pretreated wastewater then

flows to an absorption field to percolate into the soil. While a properly designed system filters out organisms, these systems do pose a potential nutrient pollutant source to groundwater, especially nitrates which move with the water through the soil profile. The septic tank must be pumped out every two to five years, depending on its size and the water use activity in the house. The solids and liquids pumped from the tank are called septage. The composition of septage varies widely (Machmeier and Moore, 1980). Typically it contains no heavy metals and very few organic compounds, but it resembles sewage sludge in its solid, nutrient and pathogenic organism content. Septage handling and treatment requirements vary from state to state, but most of it is transported to municipal sewage treatment plants.

Wastewater is treated in three ways at municipal treatment works. In primary treatment, solids are removed by mechanical screening and gravity settling. Every 1000 gallons of wastewater yields about three gallons of primary sludge. This sludge contains about five percent solids, approximately 70 percent of which is organic matter.

Secondary treatment employs bacterial degradation of soluble organic matter. The two most common systems are trickling filters and activated sludge. After biological treatment bacterial cells settle out in basins. These processes remove up to 90 percent of the organic matter in wastewater. Twenty gallons of sludge are produced per 1000 gallons of wastewater treated. This sludge typically contains one to two percent solids, 50 to 60 percent of which is organic matter. These solids are more difficult to dewater than solids from primary treatment.

Tertiary, or advanced wastewater treatment systems are primarily utilized to remove nutrients from the wastewater, something the first two treatment systems are not designed to do. Tertiary systems utilize chemical precipitation and filtration and also produce a sludge--about ten gallons per 1000 gallons of wastewater treated. The exact nature of the sludge depends on the

content of the incoming wastewater and the kind of chemical treatment provided. These sludges typically are quite wet, having a solids content of around one percent, approximately 40 percent of which is organic matter. This low organic content is in part a result of chemical treatment.

When a municipal wastewater treatment plant employs all three levels of treatment, it will generate approximately 33 gallons of sludge for every 1000 gallons of wastewater treated (EPA, 1989). This material is quite wet with solid content ranging from one to six percent. The solids are about 50 percent organic matter and contain all the macro nutrients (nitrogen, phosphorus and potassium), helminths, protozoa, and pathogenic bacteria and viruses.

Several processes can be employed to reduce the moisture content of this sludge. These range from rather simple and cheap sludge thickening processes to more complex vacuum filtering systems that produce a "dry" cake with a solid content of 20 to 30 percent.

Composting with Sewage Sludge

Composting is a biological process in which organic matter (volatile solids) is degraded to a relatively stable humus-like material. The process can be both anaerobic (without oxygen) and aerobic (with oxygen). Most modern composting is aerobic. Aerobic composting is a natural process occurring, for example, in forest litter. Several factors can be controlled to speed up and increase the efficiency of the composting process for treatment of sludge. These factors include oxygen content (aeration), moisture content, nutrient composition and balance, and temperature.

Aeration--In an unturned pile, bacterial composting begins aerobically and becomes anaerobic when available oxygen is exhausted. Bacteria degrade organic matter faster and more efficiently with oxygen and the aerobic process does not produce the foul septic odors so commonly associated with anaerobic decomposition. To keep the process aerobic, it is necessary to continuously or intermittently provide oxygen to the compost. This is usually done by pumping

air into the pile or by mechanically mixing and turning the material (every five to fifty days) using commercially available machines. The frequency depends on the activity level or stage of decomposition.

In large scale composting, material is commonly piled in windrows, or "static piles" six to eight feet high. Temperature is an index of activity and oxygen availability, and is used to determine when the windrow should be turned to aerate the mixture.

Often material to be composted is placed over a base of coarsely chopped wood chips. This base provides a piping that distributes oxygen to the pile, eliminating the need to mix or turn the windrow. Fans are used to blow air into the material. Chopping or grinding the wood chips would increase the surface area, but the smaller particles would pack together reducing void space and available oxygen.

Another composting technique makes use of a large, slowly rotating drum as well as fans. Materials turn in the drum for two to ten days. The same thing can be done in a bin called reactor vessel. A commercial system operating in Ohio composts beef cattle manure with sludge, sawdust and wood bark in a reactor vessel (Hansen and Mancl, 1988).

Moisture Content--Moisture is critical to composting. Sewage sludge adds moisture as well as nutrients. The desired moisture content of sludge depends on the moisture content and volume of other material (leaves, wood chips). The moisture content (computed on a wet weight basis) for optimal composting is 50 to 60%, although this will vary somewhat depending on particle size and aeration technique. Higher moisture content reduces the space for oxygen, and material that has a small particle size may require more aeration. However, moisture contents much below 50% can stress normal bacterial functions.

Nutrients--Nutrient composition refers to the balance of carbon, nitrogen and phosphorus in sludge organic matter. Bacteria, actinomycetes and fungi require these elements for growth. As a rule of thumb, the optimal nutrient balance for sewage sludge in treatment plants is 150:5:1. The numbers refer respectively to carbon (expressed as biochemical oxygen demand), nitrogen, and phosphorus. The recommended carbon/nitrogen ratio for composting is between twenty and thirty to one.

As the ratio includes more carbon the rate of organism growth-composting activity slows. As the nitrogen value in the carbon:nitrogen ratio decreases below 20:1 the composting process is not increased or reduced, but excess nitrogen is converted to ammonia and lost to the atmosphere. In most composting operations, the organic matter (such as leaves and wood chips) is high in carbon and low in nitrogen, and nitrogen is the rate limiting parameter. Sewage sludge is supplied to provide the nitrogen source and speed the process.

Temperature--Composting activity increases as the temperature rises. Heat is also a by-product of the degradation process. Temperatures can increase to 150 degrees F in three days of composting some materials. Each of the hundreds of different bacteria, actinomycetes and fungi active in composting has an optimum temperature range. Microbiologists divide these organisms into three broad groups based on their temperature ranges for ideal activity levels. Those labelled psychrophilic are most active at temperatures below 40 degrees F; mesophilic organisms are most active between 40 and 100 degrees F; and thermophilic organisms between 100 and 150 degrees F.

A composting operation usually involves biological activity within all these temperature ranges. Initially, psychrophilic organisms are the primary composting agents. As they multiply and continue to grow, the heat they produce increases the temperature beyond their ideal range. Mesophilic organisms start to grow rapidly and dominate the population until they, too begin to die out at even higher temperatures. The rate of composting peaks between 120 and 130 degrees

F. At these elevated temperatures weed seeds and pathogenic organisms are killed. Composting continues at a rapid rate until some required parameter is exhausted. This is commonly oxygen and the pile or windrow will need to be mixed or aerated.

An Example--Perhaps the best and certainly the largest example of composting sewage sludge using wood chips as the bulking agent occurs in Philadelphia (Gruber, 1988). The system currently processes 1,000 wet tons of sludge cake a day, mixing it with twice that volume of wood chips. Between 80 and 90 percent of the wood chips are recovered from the cured compost. Only a third of the compost is screened for sale, mostly to the commercial market. The rest is utilized in land reclamation or agricultural activities. This system serves as an excellent example of what can be accomplished on a very large scale.

Municipal solid waste is often mixed with sludge in the composting process, but its preprocessing increases the cost of the operation. Refuse must be segregated, reduced in size, composted, and then subjected to screening and magnetic separation to produce a uniform product (Glaub et al., 1984). Size reduction is the most costly step in the process.

SLUDGE MANAGEMENT PRACTICES

There are several methods currently in place to use or dispose of sewage sludge generated in the United States (U.S.EPA. 89). The greatest volume (40%) is disposed with other solid wastes in municipal landfills. A small fraction (just over one percent of the sludge) is buried in trenches at "monofills", landfills accepting only sewage sludge. No attempt is made to utilize the nutrients in sludge at landfills. Over time, anaerobic decomposition of the organic matter produces methane gas, which has an economic value and is being recovered from some older landfills.

Another 21% of the sewage sludge is incinerated at high temperatures, a process that destroys many organic compounds. Of this fraction, most is lost in the combustion process; however, almost 10% of the volume remains as an ash, which must be disposed of in a landfill. There are some concerns with incineration; emission standards do exist to ensure an acceptable air quality around the incinerator. The cost and efficiency of this process is in part dictated by the moisture content of the sludge delivered to the incinerator.

Currently over 5% of the sludge generated is disposed of by dumping in the ocean. The one site approved by the EPA for dumping is located just over 100 miles east of New Jersey. Several municipalities use this site. In 1988 the President signed legislation extending this practice until December 31, 1991 when all such disposal will cease.

About 15% of the sewage sludge is applied to agricultural land as a soil conditioner and low grade fertilizer. It is used for all types of crops including pastures, grains and row crops. There are mandatory waiting periods between sludge spreading and growth of crops harvested for animal feed, indirect and direct human consumption. Another land application site which shows promise is the spreading of sludge on non-cultivated land, primarily forestland in the Pacific Northwest. The University of Washington has done extensive research on the rates and value of forest applications. Sludge is also applied to mining and dredging spoils as part of the land recovery process.

About 9% of the sludge is processed, distributed and marketed. Processing usually involves composting to reduce pathogens, weed seeds, and odor, and mixing with bulk material such as bark or wood chips. The resulting attractive soil amendment is used mainly on lawns, parks, golf courses and by the nursery industry.

Of the above sludge management practices, ocean dumping will no longer be an option after December 31, 1991. For land fills it is likely that the hauling costs to acceptable sites will place economic burdens on this practice that will reduce its use. While there will continue to be land filling of sludge, the trend will be towards less tonnage. The EPA's analysis indicates that incineration poses more carcinogenic risk than do other use or disposal methods for sewage sludge. These concerns will raise serious questions over the construction of new facilities. While most of the existing plants will continue operation, it is unlikely this practice will experience growth. The two practices that will expand will be land spreading and processing, distribution and marketing. Land spreading is clearly a method that offers a positive use and will experience the greatest growth. It has advantages for both large and small facilities and does not require expensive, complicated technology.

The concentration of organic and inorganic chemicals in sludge that is applied to the land is also of concern, and the list of chemical pollutants applied with sludge is growing. These chemicals are found in domestic and industrial wastewater as well as the runoff from streets, parking lots, and lawns and fields treated with agricultural chemicals. Heavy metals, such as cadmium, copper, molybdenum, nickel and zinc accumulate in plants and may pose a hazard to plants, animals, and in some cases, humans. The Environmental Protection Agency is currently circulating proposed rules to limit the loading of 28 chemicals (U.S.EPA. 1989), twenty-five of which would have to be considered in land application of sludge. The concentrations of these pollutants in the sludge would be monitored and too much of any one of them would limit the total allowable application on a specific site. For some there would be both annual and total loading limitations.

Using both an annual and total loading limitation to a specific site requires compliance with two different criteria. For example, the annual loading rate of cadmium to a site varies with the crop. The annual loading changes depend on whether the crop is a food-chain crop for humans or animals. It also is influenced by the characteristics of the soil, namely the pH and the cation exchange capacity.

The total site capacity is the limit that the soils of the site should be subjected to for the long term loading. Most of the heavy metals are stable and do not move rapidly from a site. These limits ensure future land owners the ability to utilize the site for other than very limited agricultural uses into the next generation.

AGRICULTURAL USE OF SEWAGE SLUDGE AND RELATED PRODUCTS

The composting and marketing of sludge is experiencing some growth. Because of the added expense of processing the material requires an increased return to make the system economically viable. Unfortunately this cost, together with its low fertilizer value makes it unattractive to widespread use in production agriculture. The major outlet for composted produced are horticultural application in the lawn, garden and nursery industry.

In addition to sludge, sewage treatment plants also produce a treated wastewater. While the characteristics, and use of this effluent in agriculture is beyond the scope of this paper, it should be noted that agricultural application has become a consumer. Research on the value of effluent to crops and forestry, as well as the pollution potentials have been studied by researchers at Pennsylvania State University for 20 years. The land application of wastewater for treatment, utilization and recycling has been used in Muskegon county, Michigan for over ten years (Pound, et al., 1984). Crop production has been successful and the project is just one large example of positive agricultural applications of sewage treatment plant effluent.

The application of sewage sludge to agricultural lands is increasing, in part because of the cost of landfilling waste. In Dade County, Florida, the value of sludge to agricultural and other interests exceeds handling costs (Campbell, 1985). Chicago applied over six hundred thousand dry tons of sludge solids to farms from 1971 to 1983 (Hall et al., 1985). Idaho, Ohio, Vermont and Washington indicate that over half of their sewage sludge is land applied (Goldstein, 1986). Maryland applies over 90% of its sludge to the land. Manson and Wideman (1984) attribute part of the success of land applications in Ohio to a 1977 publication of the Ohio Cooperative Extension Service and the Ohio Agricultural Research and Development Center. This document describes the proper agronomic use of sludge. As a result, and as contractors who distribute and apply sludge have raised their standards, land application has won the trust of both the agricultural community and municipal decision makers.

Some large cities are considering increasing the agricultural use of sewage sludge, although it is not always the cheapest option in the short run (Crites and Richard, 1987). A new 25-year master plan for San Diego, CA shows that even though handling costs per dry ton will go up, agricultural use will increase because of metropolitan growth, and because a directive from the California Coastal Commission is forcing a relocation of the current sludge drying operation. As other sludge disposal alternatives grow in cost, agricultural uses will become more attractive.

The health aspects of land application of sewage sludge is always an issue of public concern. Wallis et al., (1984) conducted a series of experiments to address the potential threats to public health from sludge spreading. They studied plots where sewage was injected; where it was spread over grass; a pasture grazed by cows; and soil taken from a control hay field. No sludge was applied to the pasture or hay field. They found that the sludge plots compared favorably with the control (unsludged) hay field with respect to the occurrence and survival of nematode parasites, enteroviruses, and primary bacterial pathogens. Secondary bacteria pathogens persisted in all fields throughout the study, but levels declined most slowly on the sludged grass plot.

Despite the persistence of secondary pathogens, the health hazards to humans and animals of sludge spreading were judged to be comparable to those posed by a hay field and a pasture that had not been sludged.

However, because most crops are directly or indirectly consumed by humans, sludge must be processed to significantly reduce pathogens before spreading. This can be done with anaerobic digestion, air drying, lime stabilization and composting. Specific times, temperatures and conditions characterize each process. Depending on the crop and required time lag between spreading and harvest, other processes may be required to further reduce pathogens. These include more complete and higher temperature composting, heat drying, irradiation and pasteurization. These pretreatment processes, along with control of access to the site, and a mandated lag time between spreading and crop harvest are designed to prevent contamination of our food chain and water supply.

Some initial assumptions underlying the design of agricultural use systems have proven incorrect. For example, the organic nitrogen mineralization rate at a 153 ha sludge farm near Fort Collins, CO appears to be higher than the design assumption (Houck et al., 1987). The total amount of nitrogen that can be applied may have to be reduced. In fact, to maximize crop yield some commercial fertilizers may have to be applied. This type of review is beneficial as it expands our understanding of the processes involved and also builds public trust.

While there are documented advantages to spreading sewage sludge on agricultural lands (table 2) public acceptance of the practice must first be won. Hunt (1986) describes how to implement a successful plan from a public relations perspective. Walker (1986) reviews his experience using public relation skills and scientific data in an article entitled "Winning Strategies for Land Application." In it he shows how data from other operations together with public meetings can quiet public concerns.

Site Selection and Application Management

Any agricultural land is a candidate to receive sewage sludge, however, several physical factors must be evaluated to determine the suitability of the site. These factors include slope, soil depth, presence of restrictive layers, organic matter content, water holding capacity, and soil texture as it influences infiltration rate and permeability.

The rate of application is usually dictated by the nutrient and metal content of the sludge, together with site characteristics, any one of which could limit the total quantity of sludge applied, and/or narrow the application time window. Since there are few ideal sites, an understanding of site limitations and of how these affect sludge utilization and site management is important.

Slope--Movement of sludge is least likely from flat sites with nearly zero slope. As slope increases, so does the opportunity for runoff from the site (Basin and Ryan, 1985). To reduce the effect of slope, application can be scheduled during the drier season when heavy rains are rare. Smaller, more frequent applications would also reduce potential loss in runoff. A dewatered or drier sludge has less runoff potential than one with low solids/high moisture content.

Soil Characteristics--Applying a high moisture content sludge on a very sandy soil can result in rapid movement through the soil profile and losses from the system by deep leaching. The same sludge applied on a sloping clay site may be lost in runoff. On rolling sites, sludge may accumulate in low pockets, reaching concentrations that kill the crop.

The deeper a soil is, the greater its capacity to hold nutrients and other constituents of sludge. A shallow soil (and/or a high water table) may limit the quantity that can be applied, or mandate small applications on a more frequent schedule. The same is true of soils that have very

high or very low infiltration characteristics. Restrictive layers of hard pan or other low permeability soil, for example, can impose application limitations. In some cases ripping the soil with a chisel can remove this restriction.

A soil's content of organic matter, its pH and cation exchange capacity also affect its ability to hold and slowly release nutrients and other compounds, and thus directly influence application rate. A soil's capacity to hold positively charged ions like calcium and potassium increases with its negatively charged surfaces. Soils with high clay and organic contents typically have high cation exchange capacities and hence can tie up metals relatively efficiently. Huddleston and Ronayne (in press) provide an excellent review of the role of soils in site selection for the beneficial use of sludge.

Determining Sludge Application Rate

In agricultural uses of sewage sludge, application rates per acre are usually calculated to meet agronomic nitrogen requirements, taking into account the nitrogen content of the sludge (per gallon or per dry ton), and the expected mineralization rate of nitrogen in raw, digested and composted sludge over a five-year period (table 3, Crites, 1985). Application should also be timed to match the crop uptake and the soil's ability to hold the nitrogen until the crop can utilize the nutrients.

Heavy metals are also common in sludges, however, and the annual and total amount of each metal that can be applied at a given site are limited. The heavy metal components are evaluated and the most limiting constituent dictates land application parameters, a concept very well explained by Overcash and Pal (1979). Once the optimal application rate based on a crop's nitrogen needs is known, the amount of a given metal that would be applied per year at those rates can be calculated from the concentrations of that metal in the sludge. The concentration of cadmium in a sludge, for example, can be used to determine how much of that heavy metal would

be applied per year at optimal application rates based on a wheat crop's nitrogen needs (see Appendix A). The number of years sludge can be applied to the field at that rate before the cadmium concentration limit is reached is cadmium's "site life." If the exact concentration of a heavy metal or organic compound is not known, "worst case" and "typical" levels can be used to calculate its expected site life (Sommers and Barbarick, 1985).

These calculations should be repeated to determine the site life of zinc (Zi), copper (Cu), nickel (Ni) and lead (Pb) as well. The element with the shortest site life determines the sludge loading limit. An excellent review on the fractionalization, extraction, and characterization of heavy metals in sewage sludge was prepared by Lake, et al., (1984). This article suggests that researchers and lawmakers should base application guidelines on "available" rather than "total" concentrations of heavy metals. This implies that the nonspecific nature of the chemical extraction methods employed today masks the distribution of a given metal between its various fractions. With better assessment we can measure the "available" fraction, which is of concern.

Several other researchers have evaluated the release rates and availability of elements in sludge applied to certain crops. As one might expect, the release and uptake depends on the sludge and its metal concentration, soil (pH and CEC), and crop and stage of growth when the measurement was taken. With limited research results it is difficult, if not impossible, to generalize on these results. Rappaport (1986) evaluated zinc uptake in corn at fourteen sites in four different locations. Soil and plant tissue samples were taken to learn where zinc would be found in the corn plant and in what form and quantities. These studies were expanded in a second set of experiments; corn was again used to determine the uptake of Cd, Cu, Ni and Zi (Rappaport, 1988). Several application rates on different soils were used to determine metal availabilities.

Day and Thompson (1986) evaluated the value of sewage sludge as fertilizer on wheat in Arizona. In general they found that sewage sludge only and N, P and K at rates equal to the sewage sludge were taller and produced larger grain yields than wheat grown with suggested N, P

and K values of commercial fertilizer. However, grain grown and fertilizer from sewage sludge contained more zinc, lead and nickel than the other two fertilizer treatments (Table 4). The authors conclude that the data suggests that sewage sludge can be used to produce a high quality wheat grain for livestock feed that will not contain excessive amounts of cadmium, zinc, copper, lead and nickel. The conclusions from these research reports are not transferrable to another crop. Keefer et al., (1986) conducted similar studies with vegetables grown in soil amended with sewage sludge. While metal uptake levels were not alarmingly high, they indicate a need for a better understanding of total elemental analyses on crop ground. Chakrabarti and Chakrabarti (1988) studied the effect on wheat of irrigating with raw and diluted sludge. The grain enrichment efficiencies for Cu, An and Mn were significantly low under all experimental conditions. However, grain enrichment efficiency for Cr was low under all sewage irrigation conditions only. The well water with settled sewage sludge produced higher values.

It had been assumed that heavy metals accumulate in the upper soil profile or cultivated layer, which is why availability and plant uptake rate are so important. However, there is now evidence that these elements solubilize and move down through the soil profile. In laboratory studies digested sewage sludge was mixed with different soils and incubated at 25 degrees C for up to 30 weeks (Dudley, et al., 1986). The movement and availability of metals and other sludge constituents were monitored. The study revealed that carbon, copper, nickel and zinc did move; their solubility varied with pH changes over the incubation period.

Schirado, et al., (1986) gathered field samples from sites where untreated municipal wastewater had been applied for five decades. There was strong evidence that some of the heavy metals had moved beyond the cultivated layer, and thus become unavailable for crop uptake. That was the good news. However, the movement of heavy metals into the deeper soil profile and ultimately groundwater raises new questions and concerns about the land application of sewage sludge.

While much work has been done to understand the fate of heavy metals in sludges, the fate of organic compounds has received little attention. Demirjian et al., (1987) followed the fate of some 25 organic compounds from plots sampled 5, 122 and 241 days after sludge application. When applied at rates less than 224 072 Kg/ha (100 dry ton/ac), most compounds degrade considerably during one irrigation season. At less than one quarter of the above rate, most compounds degrade to less than 50% of initial concentration. From the concern of organic concentrations alone, this rate seems safe for annual, repetitive applications, with continued monitoring.

Crop production may be compromised by the heavy metal content of sludges (CAST, 1976). Heckman et al., (1987B) reported a possible reduction in soybean production as a result of the heavy metals contained in the sludge applications. Some plots showed an increase in nitrogen accumulation, while others were not always positive. Results suggest sludge may enhance soybean growth, however, benefits may be limited to sludge low in heavy metals. In a companion paper the same authors (1987A) reported the accumulation of heavy metals in soybean plants. The digested sludge linearly increased shoot metal concentrations of Zn, Cd, Cu and Ni. The results indicate sludge composition and soil pH can have a substantial influence on soybean metal uptake for at least nine years after the initial sludge application. Lance (1986) measured nutrient loss rates resulting from the addition of sewage sludge to soils with different infiltration rates. In the soil column flooded with secondary effluent at an infiltration rate of 30 cm/d nitrogen loss rates increased from 22 to about 55 percent. When loaded at an infiltration rate of 60 cm/d the nitrogen removal rate almost doubled over the rate of soil before the sludge was added. The added sludge decomposes and apparently provided a steady source of C for denitrifying bacteria.

The rate of nitrogen loss from sewage sludge depends, in part, on the rate it is mineralized--broken down from an organic form to the inorganic form crops utilize. Chae and Tabatabai (1986) compared the mineralization rate of sewage sludge and animal manure and

found them similar in the same soil type. Mineralization rates can have a significant impact on crop growth. If they are overestimated, the crop will be short of nitrogen and production will suffer. On the other hand, if they are underestimated, excess nitrogen can become a pollution problem.

Chemical nitrogen availability indexes can be used to assess soil N availability on sludge treated lands if the indexes are calibrated to the local crop, soil and climatic conditions (O'Keefe, et al., 1986). In a study of the mineralization rate of sludge amended soils, Wiseman and Zibilske (1988) found that at least 70% of the total carbon mineralized in the first eleven days, at two different application rates. Nitrogen mineralization was nearly linear during the first forty days of incubation, suggesting that sludge applications should be matched as closely as possible with crop growth and uptake of nitrogen. Heavy applications of organic matter at the wrong time (i.e., in the autumn, prior to a long period of no crop use) presents an opportunity for deep leaching or surface runoff, both of which raise environmental concerns.

Jones and Hinesly (1988) compared nitrogen loss in runoff and drain tile over two years on a corn crop grown in a large- scale lysimeters receiving sludge and inorganic fertilizer. While some things can be learned, it must be noted that the average nitrogen application on the sludge plots were over eight times larger than those applied to the commercial fertilizer plots (2800 vs 336 kg/ha). Runoff, highest during early summer storms, accounted for less than one percent of the nitrogen loss from the sludge applied treatments. The tile drain accounted for the major loss mechanism of nitrogen. The average concentration of nitrate was 223 and 44 mg/l the first year for the plots with and without sludge respectively. There was also over three times the tile volume from the sludge amended plots. These differences make it difficult to draw comparisons, but do show that heavy nitrogen application can cause groundwater pollution problems.

O'Connor et al., (1986) studied the solubility and movement of phosphorus in sludge-amended calcareous soils, and found that the addition of sludge did increase soluble P and also plant uptake of P. While phosphorus is not a threat to public health, its escape can increase the quantity available to plants and algae in water systems and cause water quality problems. The movement and availability of all nutrients need to be evaluated as we study the impacts of land application of sewage sludges.

As the practice of spreading sewage sludge on agricultural land increases, new environmental impacts may emerge, and must be evaluated. Pietz, et al. (1984), evaluated the heavy metal concentration in earthworms at a receiver site, an example of one new way to evaluate the impact of sludge spreading. They found uptake of metals to be variable, and evidence that some metals may harm earthworms or their predators.

POLICY OPTIONS

Congress could provide two kinds of assistance. The first one is economic and the second lies in furthering a sound understanding of the environmental impacts of land spreading sewage sludge.

The levels of activity in land application programs vary widely from state to state. The three common sources of funding for these programs are state general funds, permit fees and grants from the EPA. These grants currently support a wide ranges of activities and could be increased to provide more assistance in site evaluation.

Not all states currently require on site visits and evaluation. Supporting this activity should result in better management and elimination of sites that are unacceptable for some reason. A better track record will encourage other communities to consider land spreading and calm fears about odors, public health threats and declining property values.

EPA grants could also fund enforcement programs involving expanded site visitation and monitoring to ensure proper management practices. Zirschky et al., (1985) have reported a wide variation in state requirements for groundwater monitoring at application sites. Stronger efforts here could promote proper practices and further build public confidence in land spreading of sewage sludge.

EPA grants could also be expanded to support operator certification schools. Funding could be directed to each states's environmental quality group, which could offer educational programs or fund them at community colleges. The expertise that emerges from such programs should further reduce the number of poorly managed sites.

Finally, funds can be made available to researchers to conduct experiments on the movement and availability of some sludge constituents that cause concern. A better understanding of the true fate and pathways of these elements and organisms, should result in better systems design and management.

Better managed sites will reduce the threat to the environment and create in a more positive image for land application of sewage sludge. In many cases, uninformed and fearful local citizens have stopped land spreading activities. Any effort to reduce the NIMBY (not in my back yard) syndrome will allow this environmentally acceptable practice to gain support and widespread utilization.

Table 1. Composition of Nutrients and Heavy Metals in a Washington, DC Area Composted Sewage Sludge

(Source: USDA, 1979)

Nutrient Components as Percent of Total	
Nitrogen	< 1.5%
Phosphorus	< 2.0%
Potassium	< 0.2%
Iron	< 4.0%
Heavy Metal Concentration in Parts per Million	
Zinc	1,250
Copper	500
Cadmium	12.5
Nickel	200
Lead	500
Mercury	5

Table 2. Advantages of Utilizing Sewage Sludge on Agricultural Lands

- Sludge contains significant amounts of plant macro nutrients (N, P, and K). There are also valuable levels of micro nutrients that are beneficial to plant growth.

- The addition of sludge serves as a soil conditioner and increase water and nutrient holding capacity, increase pore space and adds to the tilth of the soil.

- Applications occur in the rural areas when spreading fertilizers is not uncommon and accepted by the local population.

- The receiver systems is owned by local agriculturists and this reduces the cost of owning the site for the municipality.

- This land application is usually the cheapest sludge management practice available to the municipality. All the community wins by lower costs.

Table 3. ORGANIC NITROGEN MINERALIZATION RATES

(Source: Crites, 1985)

(Percent of Total Mineralized per Year)

Year	Raw or Waste Activated	Anaerobically Digested	Composted
1	40	20	10
2	20	10	5
3	10	5	3
4	5	3	3
5	3	3	3

Table 4. Average concentrations of heavy metals in grain from six wheat cultivars grown with three fertilizer treatments at Mesa, Arizona in 1983

(Day and Thompson; 1986)

Fertilizer treatment	Cadmium	Zinc	Copper	Lead	Nickel
	_____ mg kg-1				

Suggested N, P, K from commercial fertilizer	0.4+	31.6 b	10.6 b	1.4 b	10.5 b
Sewage sludge to provide suggested N with no additional fertilizer	0.6 a	45.3 a	12.0 a	4.5 a	22.4 a
N, P, K from commercial fertilizer equal to sewage sludge	0.5 a	34.8 b	11.5 a	1.6 b	14.9 b

+Means, within columns, followed by the same letter are not different at the 5% level of significance.

APPENDIX A

EXAMPLE OF SITE LIFE CALCULATION OF CADMIUM

A sample calculation illustrates how the site life of cadmium can be determined if its loading limit is 4.46 pounds per acre. Sludge production is 6.38 million gallons per year. The sludge is 2.41 percent solids. Cadmium concentration is 55 parts per million, and total Kjeldahl nitrogen (TKN) is 8.9 percent. The recipient wheat crop can utilize 100 pounds of nitrogen per acre per year. In this example, it is assumed that the TKN is all of the nitrogen in the sludge; that there are no

application losses; and that all of the nitrogen will be available in the first year.

Lbs. solids per year

6.38 milliongal/yr x 8.31lb/gal x 0.0241lb solids/lb sludge = 1,278,000lbs solids applied/year

Annual nitrogen production

1.278 millionlbs solids/yr x 0.089lbN/lbs solids = 113,742lb nitrogen applied/yr

Nitrogen application to wheat

(113,742 lb N/yr) / (100 lb N/acre) = 1137 acres of wheat

Cadmium application to wheat

1.278 millionlbs solids/yr x 55lb Cd/1 million lb solids = 70lbs Cd applied/year

Cadmium application per acre

(70 lb Cd/yr) / (1137acres wheat/yr) = 0.062lb Cd/acre/year

Cadmium site life (based on 4.46 lbs/acre)

(4.46lb/acre) / 0.062lb Cd/acre/yr) = 71.9 years (site life of cadmium)

Thus, the cadmium site life of sludge with these characteristics on a wheat crop is approximately 71.9 years.

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THE ROLE OF RETAIL FERTILIZER DEALERS IN REDUCING GROUNDWATER CONTAMINATION: A FOCUS ON EDUCATION NEEDS

by

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PREFACE

TVA conducts programs to deliver research results from its National Fertilizer Development Center (NFDC) to fertilizer manufacturers and marketers and ultimately the American farmer. In so doing, the Center works with hundreds of fertilizer producers and dealers to solve problems facing the fertilizer industry and agriculture. This joint effort has made it possible for NFDC to meet its program objectives of introducing new and improved fertilizers and processes and promoting efficient fertilizer use. The fertilizer dealer has played a key role in educating farmers to use fertilizers both effectively and efficiently since the inception of TVA's programs.

This paper was developed for the Office of Technology Assessment's study, "Agricultural Approaches to Reduce Agrichemical Contamination of Groundwater," and will serve as a background document for educational needs of fertilizer dealers. The authors do not consider the paper a definitive defensive work but rather a logical argument to identify the retail fertilizer dealer as a key link between basic fertilizer/chemical manufacturers and the farmer. Therefore, the educational needs of this retailer is the salient issue of the paper.

THE ROLE OF RETAIL FERTILIZER DEALERS IN REDUCING GROUNDWATER CONTAMINATION: A FOCUS ON EDUCATIONAL NEEDS

by

Ronald J. Williams and James M. Ransom*

Introduction

Retail fertilizer dealers are a critical link in the U.S. agricultural production complex. They are positioned to have major impact on annual fertilizer and pesticide use decisions involving over 44 million tons of fertilizer materials and 470 million pounds of active ingredients of pesticides (USDA, 1989). These inputs are key targets in efforts to reduce agrichemical contamination of groundwater. Therefore, the dealer's ability to positively influence the farmer's decisions concerning use of these inputs could greatly impact the reduction of groundwater contamination.

The purpose of this paper is: (1) to focus on the role of the fertilizer/agrichemical dealer in this effort, (2) to discuss educational needs of the dealer in order to operate his own business in compliance with environmental regulations and, (3) to point out the educational and motivational needs of the dealer in order to assist his farmer-customers to use agrichemicals in ways that will eliminate or reduce groundwater contamination from farming operations.

Background

On one side of the retail fertilizer dealers are industrial concerns and developers of improved agricultural technology. On the other side are final users of this technology, the farmers. The simplified flow diagram of U.S. fertilizer production and distribution (figure 1) identifies this key position (Hargett et al., 1988).

The retail fertilizer industry evolved over the years to its present organization, structure, and operational features. Early functions centered on provision of distribution services (transportation, warehousing, and packaging) for inputs in final form, whereas later evolvement is

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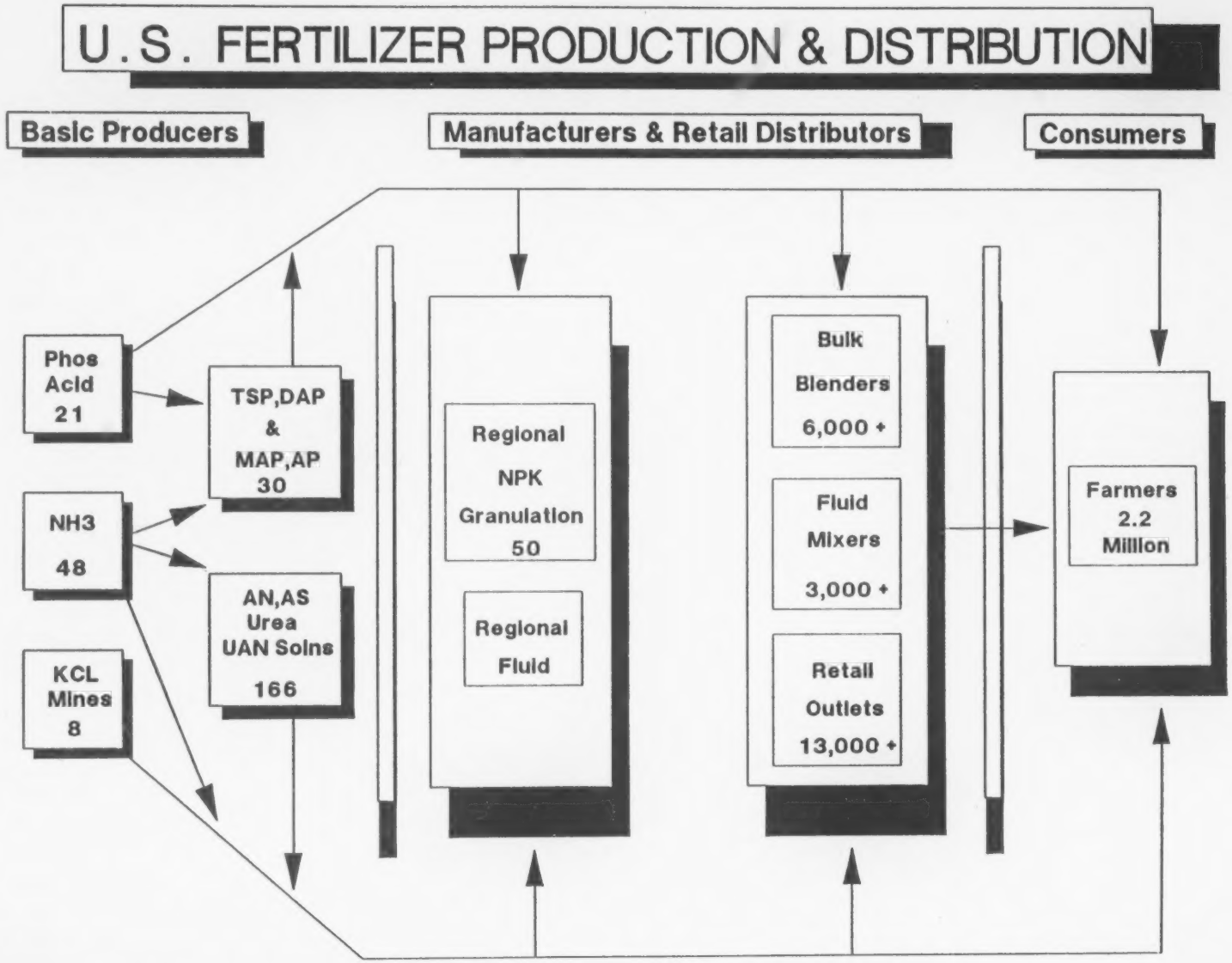
Figure 1



Figures indicate number of operating plant locations - FY 1988
Total retail outlets: 13,000 - 15,000
Association of American Plant Food Control Officials - Survey 1988

C-10

manifested by multidimensional service centers. This was brought on by dealer response to market signals and opportunities created by a continuous flow of technological developments, production advances, and changes in production agriculture. Dealers who made these changes have been successful and have grown. Educational efforts by dealers, such as soil testing, computerized crop production programs, farmer meetings, farm visits, and specific assistance in problem solving, have been keys to success in making the shift to the full-service center.

Today's fertilizer retailer supplies not only fertilizers but also a full range of production inputs and services. This includes technical information and/or recommendations on: (1) crop variety selection, (2) production alternatives and practices, (3) input characteristics and use, (4) custom blending or mixing, (5) production credit, (6) custom application services, (7) specialized equipment rental, (8) soil testing, and (9) marketing advice (this list is far from exhaustive).

The significant flow of technological advancements into U.S. agriculture caused retail dealers to make major adjustments in the mix of products and services they offer. Retail fertilizer dealers have been forced to develop educational processes, both formal and informal, to provide the knowledge and skills necessary to: (1) utilize and operate increasingly sophisticated equipment, (2) provide product use information for effective and efficient marketing, (3) remain abreast of a steady flow of technological developments and options, and (4) develop the management and marketing skills and techniques necessary to maximize returns to invested resources.

Traditionally, the product and service mix, as well as the educational activities, of retail fertilizer dealers has been oriented toward on-farm productivity. Recently, however, public pressures are necessitating the development and implementation of an increased environmental sensitivity--a sensitivity not only for improving the environmental performance of individual business operations but also for helping reduce any adverse impacts of agriculture on the environment. Thus, a duality exists which has important implications for identifying the educational needs of dealers.

First, fertilizer dealers will require new information and skills to operate their own businesses in compliance with emerging regulations and consistent with standards for improved environmental performance. Second, dealers will need to acquire the knowledge and skills that will allow them to continue to serve U.S. agriculture and, at the same time, discharge their responsibility to help minimize any adverse impacts of agricultural activities on the environment.

In the first case, the skills and knowledge required pertain to the operation and performance of individual businesses. In the second case, the new skills and knowledge are needed to help motivate and assist farmers in using agrichemicals in a more environmentally sensitive manner. The first situation places emphasis on improving the quality and performance of internal-to-the-firm decisions. In the latter case, the fertilizer dealer acts as a change agent, placing emphasis on changing the behavior of--i.e.,

educating--farmer customers in their responsibility to help minimize adverse impacts on the environment. Both dimensions are important, but it is this second role--the dealer as educator--that is the primary focus of this paper. Additionally, the backdrop is groundwater contamination, especially nitrate contamination, arising from the use of commercial fertilizer materials and/or manures and legumes.

In short, dealers will require information and training to improve their environmental stewardship performance. At the same time, they will need to acquire the knowledge and skills that will allow them to continue to service U.S. agriculture in concert with additional responsibilities to help frame farming's new environmental agenda in order to minimize the adverse impact of agricultural activities on the environment.

Information Dissemination and the Educational Roles of Fertilizer Dealers and Others

Information Flow

Within the context of these emerging environmental issues, the land-grant university system, fertilizer and agricultural chemical manufacturers, government institutions, state and national trade associations, professional consultants, and others will need to play a vital role in providing input into production management decisions. This input will need to be extended through research, outreach/technology transfer, and labeling information. However, county extension agents are often "spread too thin" to provide the one-on-one contacts needed for information delivery and hands-on skills development for commercial farmers, part-time farmers, homeowners, and other users of fertilizer and agricultural chemicals. Further complicating the educational task is the current trend to continue reducing the numbers of county extension personnel in many rural areas (because of shortages of funds) and to overload the remaining staff with additional tasks.

Also many fertilizer manufacturers have had to reduce or eliminate their company's technical service assistance personnel. And sales staffs now cover broad areas, have limited contact with dealers and farmers, and lack the time and training necessary to provide input on technical questions from dealers. Agricultural chemical manufacturers provide relatively more intensive coverage, but their focus is typically on product-specific sales and troubleshooting. In short, limited resources (people, time, money) restrict technical and related, e.g., environmental, information to farmers to a general dimension. When the groundwater issue is added, support organizations will need to devote additional resources to help the dealer use environmental information to develop specific farm plans.

But on the positive side, while numbers of people for direct contact have been dwindling, there has been a significant increase in support available to dealers from a diverse group of institutions and

organizations. The list includes the land-grant universities, basic fertilizer and agricultural chemical suppliers, NFDC, the Potash/Phosphate Institute (PPI), fertilizer and agricultural chemical associations, state fertilizer educational societies, and others. The trade press has filled an important need by providing dealer information and selling the idea that education and service pays. Dealers, with their professional training as well as their infrastructure support, have played an extremely important role in farmer education relating to profitability of fertilizer use. Both cooperatives and independent dealers have benefited from the educational support just indicated. By utilizing this support, cooperatives have developed dealer training packages and services to benefit their dealer and farmer members. And independent dealers have used materials provided by basic suppliers and support organizations to develop information and educational aids suited to their clientele.

The support organizations mentioned have developed training programs covering a wide range of subject matter, including environmental concerns. An example of information already in the pipeline is the best management practices developed and interpreted by PPI (based on university research). And, NFDC is developing an environmental initiative specifically aimed at protecting the Nation's water resources. The three main thrusts of this initiative are secondary containment of fertilizer and agricultural chemicals, research efforts directed at preventing nonpoint source pollution, and an accumulation of information repackaged for distribution to dealers, farmers, regulators, concerned citizens, etc.

Educational Role of the Fertilizer Retail Dealer

Retail fertilizer dealers are not extraneous or unnecessary "middlemen." They fill a critical void between the "general and site-specific." As the fertilizer and chemical industries became more sophisticated in the 1960s, technically competent, full-service fertilizer centers were established in most farm communities by either cooperative or private firms. With this increased technical sophistication of fertilizer distribution centers, farmer patrons grew to rely on them as primary sources of use recommendations for fertilizers and chemicals. And today, because dealers are the final points of contact at sale, their influence on decisions is crucial to attaining any objectives related to the reduction of groundwater contamination.

General benefits to farmers from the development of full-service fertilizer centers included lower tonnages handled per acre because of high-analysis fertilizer materials, fewer trips across the field by combining fertilizer and herbicide applications, reduced investment in farmer-owned application equipment, and savings in fertilizer costs from buying least-cost formulations based on soil test results. Many farmers use dealers to buy fertilizers, chemicals, and attendant services to relieve critical labor constraints and to ration limited investment capital while choosing the correct fertilizers and chemicals to suit specific production needs. Dry bulk blending, fluid mixing, conveniences in adding secondary/micronutrients and crop protection chemicals, along with custom application, have expedited transfer of these benefits to farmers.

Substantial pressure for innovation rests on fertilizer dealers. Many farmers are unable to individually generate new technology and must rely on dealers for new innovations; or, in other words, they must be able to "buy into" sophisticated technology for relatively low individual expense. The retail fertilizer dealer plays a critical role in bringing technology from the basic suppliers and manufacturers into contact with farmers. Retail dealers are in the position to be acutely aware of local conditions and are able to get a product used to its greatest advantage. This is critical because the demand for fertilizers and agricultural chemicals is a "derived" demand, i.e., the value of an input is based on its contribution to the production process. Therefore, by recommending the most advantageous product, the retailer is helping both the basic producer and the farmer by enhancing the value of the input. Dealers who have developed substantial investments to facilitate the flow of inputs and information to a very diverse group of farmers are in the business for the long run. Thus, they know their economic health ultimately depends on the health of their patrons.

Educational Role of Others Involved

While the focus of this paper is on the dealer's role in helping reduce potential groundwater contamination, there are others, however, intimately involved with farmer education that must be recognized. Farmers are influenced by or receive information from bankers, financial planners, consultants, other farmers and farm dealers, farm organizations, the farm press, research and extension publications, house organs of corporations and related industry mailings, USDA agencies, and advertising (and this list names only some of the more obvious information and influence sources). All of these sources must be in general harmony and agreement with the ultimate environmental protection objective and must support dealers, farmers, and professionals as they perform their respective roles in this effort.

Farm policy will need to be re-evaluated in terms of this objective, along with other considerations. State regulatory officials and other state agricultural agencies will need to lend support and adjust policies as needs dictate. Above all, because of potential negative messages concerning the groundwater protection issue, the organizations and institutions providing basic leadership and information to dealers must support the environmental initiative, as well as supporting and rewarding employees working in the environmental area.

Educational Issues and Needs in Groundwater Protection and Challenges for the Retail Dealer

Educational Issues

Groundwater protection--a new challenge--takes on two dimensions for the dealer. First, the dealer must meet new environmental compliance

requirements onsite and operational requirements both on- and offsite. Second, the dealer must motivate and help customers reduce any adverse environmental impacts on groundwater from agricultural operations.

Emerging issues which will continue to impact the operational environment of the dealer include: (1) dealer/plant compliance with federal, state, and local regulations in the areas of waste minimization, containment, and disposal--to minimize, contain, and dispose/degrade dilute fertilizer and pesticide wastes from spills at loadout areas and from washing nurse tanks, application equipment, tanker trailers, and bulk and prepackaged pesticide containers; (2) site cleanup of areas which have been contaminated from previous waste disposal practices; and (3) dealer concern with future liability for advice and recommendations of practices to farmers. Pressure for increased knowledge of nitrates, pesticides, chemigation, field monitoring, heavy metals in fertilizers, air quality, and health and safety of employees will be paramount (Culp et al., 1988).

Items of utmost importance to dealers in working with farmers on groundwater protection issues will be the dealer's need to become increasingly aware of environmental concerns and how these can shape specific individual needs. These needs will include: (1) the ability to educate the farmer in the potential adverse environmental impact of fertilizer and crop protection chemicals and the need to implement best management practices; (2) a deeper understanding of basic sciences involved in crop production and how to educate the farmer in these areas; (3) an understanding of the internal/external impacts of production costs and benefits; (4) an understanding of policy and regulation processes, along with methods for communicating these to clients; (5) access to information on product characteristics, features, and impacts; and (6) an understanding of the demand for inputs and related information needs.

Dealer Education Needs

Earlier in the text of this paper we emphasized the fact that in the past the focus of all concerned has been toward increasing production, yields, and income of the parties concerned, as well as improving the economic well-being of the Nation. Work in this area has been self-fulfilling and relatively risk free in terms of the concerns of people involved. This situation will change when groundwater protection and other environmental constraints are met, along with regulatory requirements in other fields.

Now, increasing emphasis is being placed on the potential adverse effect of fertilizer and chemical use, notably groundwater contamination, which has become apparent only with the passage of a significant period of time. This increased emphasis toward groundwater protection suggests rather dramatic changes in the underlying market strategy of fertilizer and crop protection inputs. Of necessity, fertilizer and other agricultural chemicals are marketed based on their value to current production, seldom more than one to two years. This is short-range and both fertilizer dealers and their farmer-clients can identify the benefits, with both being driven by very similar business and personal motives. Relevant questions to ask

are: (1) Could similar motivation be harnessed to encourage activities to maintain or enhance groundwater quality, where the payoff is not so readily apparent? and (2) Does the fertilizer dealer have a role in helping reduce groundwater contamination? We believe a sound case has been made that dealers do, indeed, have a role and that it must be an important role. Therefore, let us turn our attention to questions of harnessing the motivation.

It is apparent that most fertilizer dealers will not identify immediate pecuniary benefits from adopting a proactive groundwater education program, and may in fact, fear that it will evoke a negative reaction from the broader community in concentrated agricultural areas. It must be realized that farmers and fertilizer dealers alike have significant investments--financial, human, and personal/professional--and naturally will be reluctant to dramatically change production and operating practices that increase risk, either real or imagined. Both have legitimate concerns that must be overcome before motivation can be harnessed. From the dealer perspective, several factors are important to developing and implementing such a strategy.

First, an educational effort must be undertaken to increase dealer sensitivity to environmental issues in general and to those associated with agricultural activities in particular. If there is not a sensitivity to the issue(s), little impact will be made and little, if any, responsibility accepted. The concept of stewardship must be clearly established.

Second, a link between the environmental consequences, economic well-being of farmer customers, and the long-term economic viability of fertilizer retail operations must be logically established and reasonably demonstrated. Dealers have a basic long-term interest, especially those surviving the recent economic depression in agricultural economy, but they will need support and guidance in making short- versus long-term tradeoffs.

Third, if dealers are to play a key role in educating farmers to the objective of reducing adverse environmental impacts from agriculture, they will have to be provided with a process for doing so, as well as with sound technical information. Traditionally, fertilizer and agricultural chemical marketing programs have transmitted a significantly different message and required a different orientation than will be required for environmental education.

Fourth, both the information and the process provided will have to promote tailoring to meet local area needs. There is a place for limited generic-type educational materials. However, U.S. agriculture is very diverse and such materials probably will have to remain so broad that the subject matter may appear trivial to many fertilizer dealers and farmers. Fertilizer dealers and farmers utilize very sophisticated technologies, albeit often embodied in rather easy to use packages. Educational materials will have to be technically correct and readily verifiable.

And finally, information and supporting materials must be presented in a manner that communicates not only with dealers but that also can be easily translated into farmer-targeted messages. Informational materials

also must be free of errors, both from business and industry operational as well as technical standpoints. Credibility will be a key factor and sufficient quality control will be necessary to prevent materials, concepts, or processes from being labeled "whimsical."

A logical question to ask at this point is, "Who should provide the information, process, and support necessary to make effective and efficient use of fertilizer dealers in educational efforts to reduce adverse impacts of agriculture on the environment, most notably groundwater contamination?" Obviously, the agencies listed previously, along with institutions, both public and private, have major roles to play. However, if the process is to be effective and the information locally relevant, major use will need to be made of those institutions currently being used in dealer education efforts. Traditionally, such dealer education efforts have been targeted toward improving management, marketing, and technical skills (both operational and agronomic practices). However, in response to emerging issues, programs of these institutions have demonstrated a significant shift toward worker safety and certification, and more recently, toward topics of emerging legislation, status, potential impacts, and compliance. The recently released Dealer Environmental Training and Information Library (D.E.T.A.I.L.) modular training program developed by Monsanto, in cooperation with selected state associations, is an excellent example. Such associations and organizations are familiar not only with the issues facing the membership but also have intimate knowledge of business operations and industry interactions/relationships. This knowledge base allows them to package educational programs in a language that facilitates message reception.

However, these organizations and institutions will require assistance in developing a process and in identifying, selecting, and packaging information necessary to: (1) facilitate development of an environmental sensitivity among dealers; (2) motivate these dealers to accept responsibility of a role in educating farmers of the potential adverse impacts of agriculture on the environment, especially the groundwater dimension; and (3) support and encourage dealer educational efforts.

A host of organizations, agencies, and institutions are visualized as potential sources of information; however, emphasis must be placed on utilizing local and cropping-system-specific information. This implies that the land-grant universities and extension service technical resources of state governments, as well as federal agencies with local offices, SCS, for example, will play key roles. Broader problem-setting or identification probably will come from a number of federal agencies, such as USDA, SPA, NFDC, and national conservation and environmental organizations.

Closing Comments

It is imperative that organizations and institutions involved in the environmental initiative gain an awareness of the importance of the

retail fertilizer dealer in information dissemination to farmers and of the related educational needs of the dealer. It is equally important that efforts to use this dealer network be enhanced by these institutions. This dealer network will not solve groundwater contamination issues, but it can provide a key link in overall educational efforts.

The more than 13,000 retail fertilizer dealers represent an important educational resource and employ a significant capital investment. Their impact on the rural infrastructure should not be ignored. They are situated at local sites, in strategic proximity to industrial suppliers and farmers. Many have large investments in manufacturing/application equipment technologies. Such labor-saving technologies can help spread high fixed costs of these technologies over many acres or other units.

But education involves improving the productivity of human capital, arguably the dealer's most important resource. Effective dealer education can adequately and efficiently lever a significant bundle of resources for addressing the myriad of new and increasing pressures for groundwater protection. In short, this education has two dimensions: (1) education for the dealers and their human capital in meeting the many new challenges from an operational perspective; and (2) education for the dealers and their human capital in meeting the site-specific information requirements and attendant education needs of their clients--the American farmers.

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